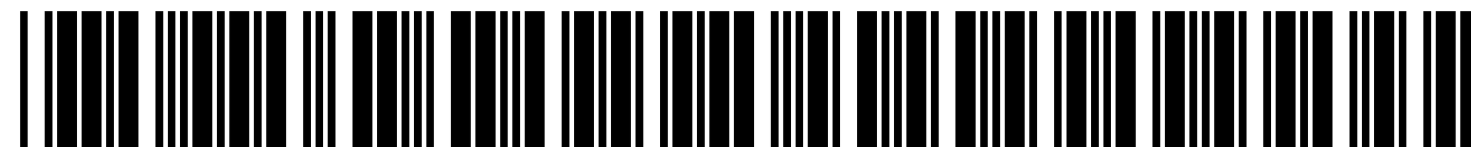

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Roizin et al.

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(45) **Date of Patent: Dec. 5, 2017**

(54) **GAS SENSING USING MAGNETIC TUNNEL JUNCTION ELEMENTS**

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(73) Assignee: **Tower Semiconductor Ltd.**, Migdal Haemek (IL)

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(22) Filed: **Dec. 3, 2015**

(65) **Prior Publication Data**

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G01N 27/74 (2006.01)
G01N 33/00 (2006.01)

(52) **U.S. Cl.**
CPC ***G01N 27/74*** (2013.01); ***G01N 33/0027*** (2013.01)

(58) **Field of Classification Search**
CPC G01N 33/0027; G01N 27/74
USPC 73/25.02
See application file for complete search history.

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(57) **ABSTRACT**

Gas sensing using MTJ elements to capture/store gas concentration level data for readout at room temperature. In one embodiment, during reset the MTJ elements are heated above blocking temperatures of their storage layers while applying a first magnetic biasing force to set initial magnetic orientations. During gas sensing, reaction heat from a gas sensing element combines with control heat to raise each MTJ element's temperature from a work point temperature above its blocking temperature only when the target gas exceeds an associated concentration level, whereby a second magnetic biasing force causes the magnetic orientation to switch directions. During readout, read currents are measured to determine the MTJ elements' final resistance states, which indicate their switched/non-switched states, and the resistance states are correlated with stored data to determine the measured gas concentration level. The MTJ elements are cooled after reset and gas sensing to facilitate accurate CDS readout data.

20 Claims, 9 Drawing Sheets

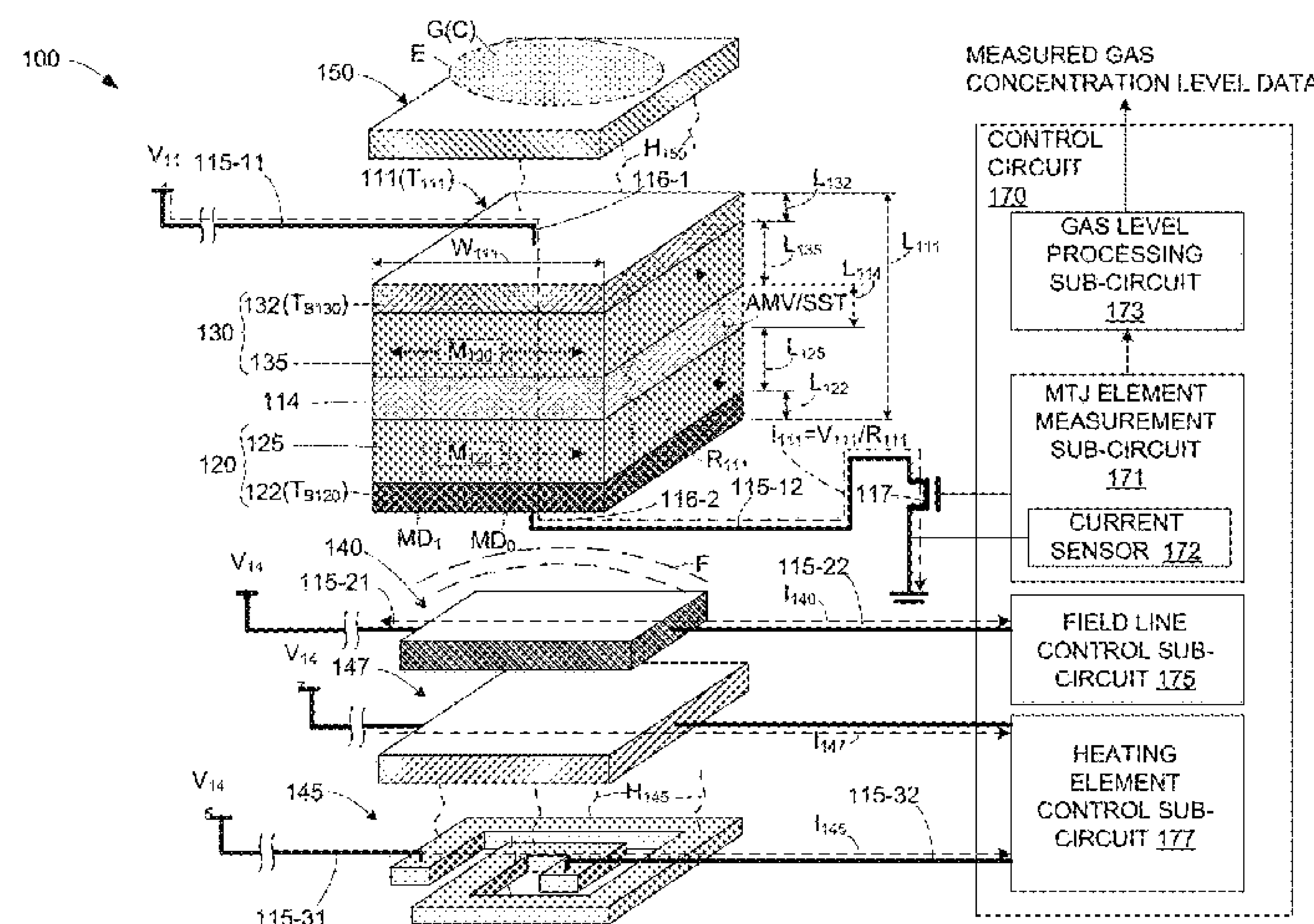

FIG. 1

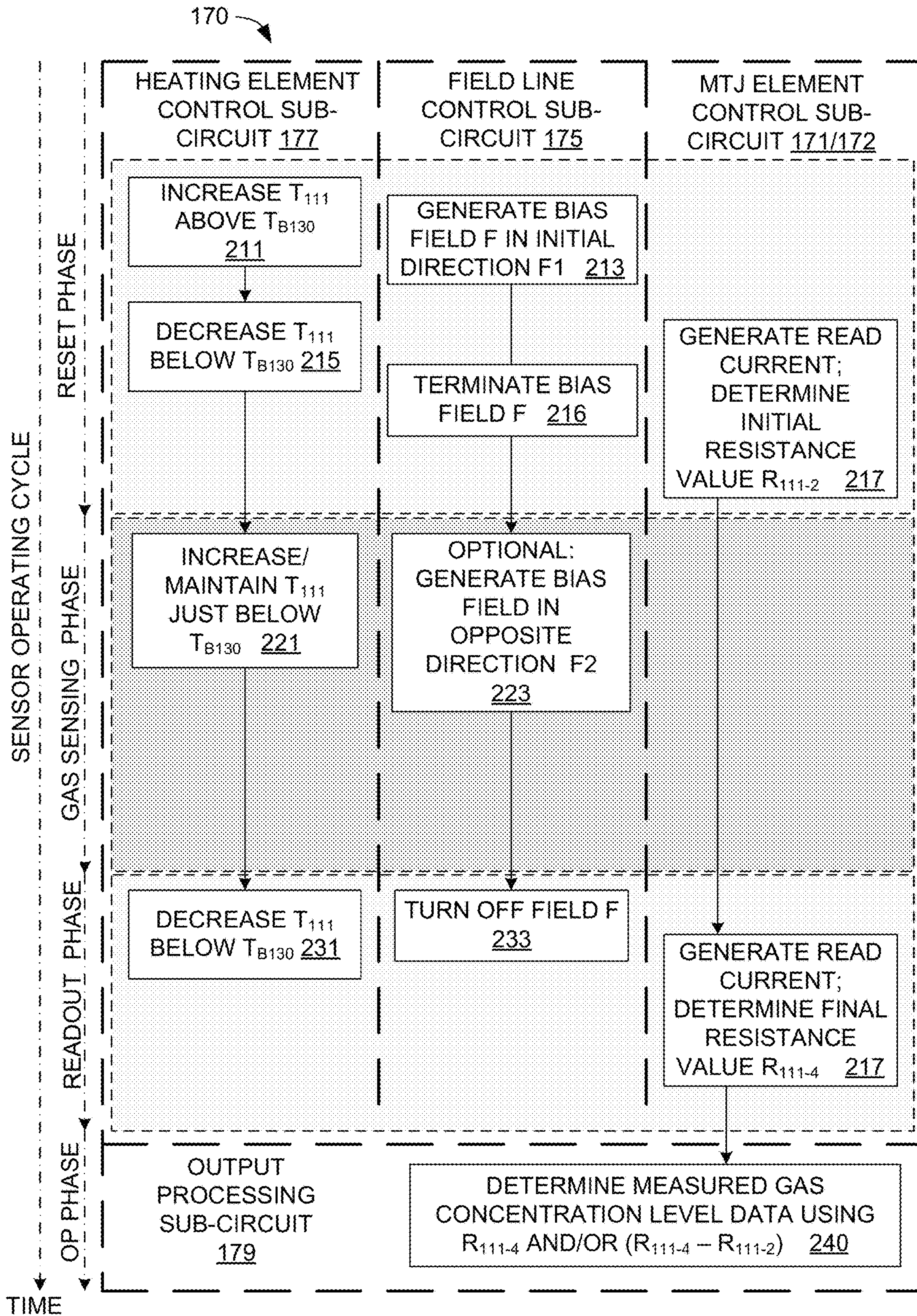

FIG. 2

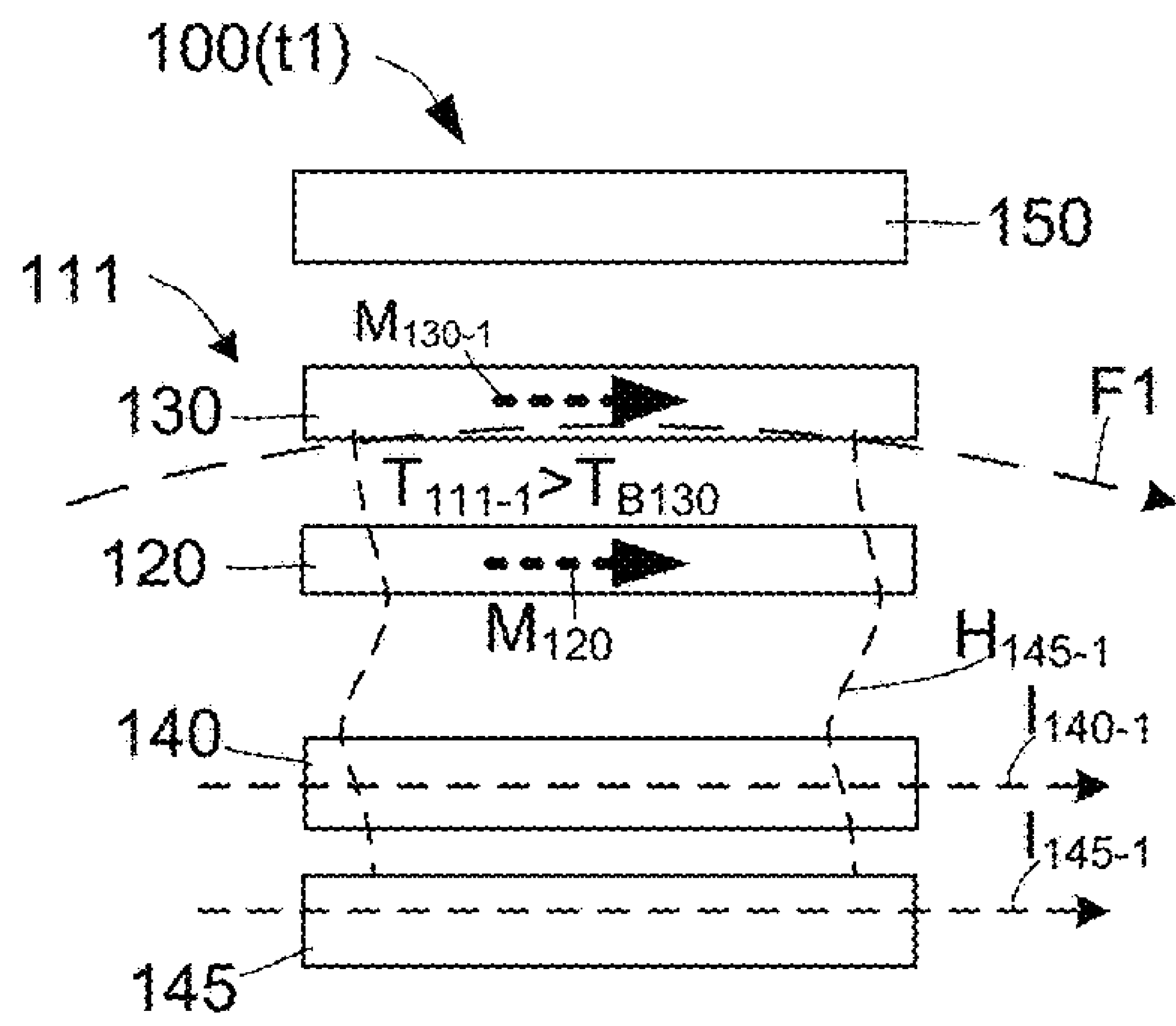

FIG. 3(A)

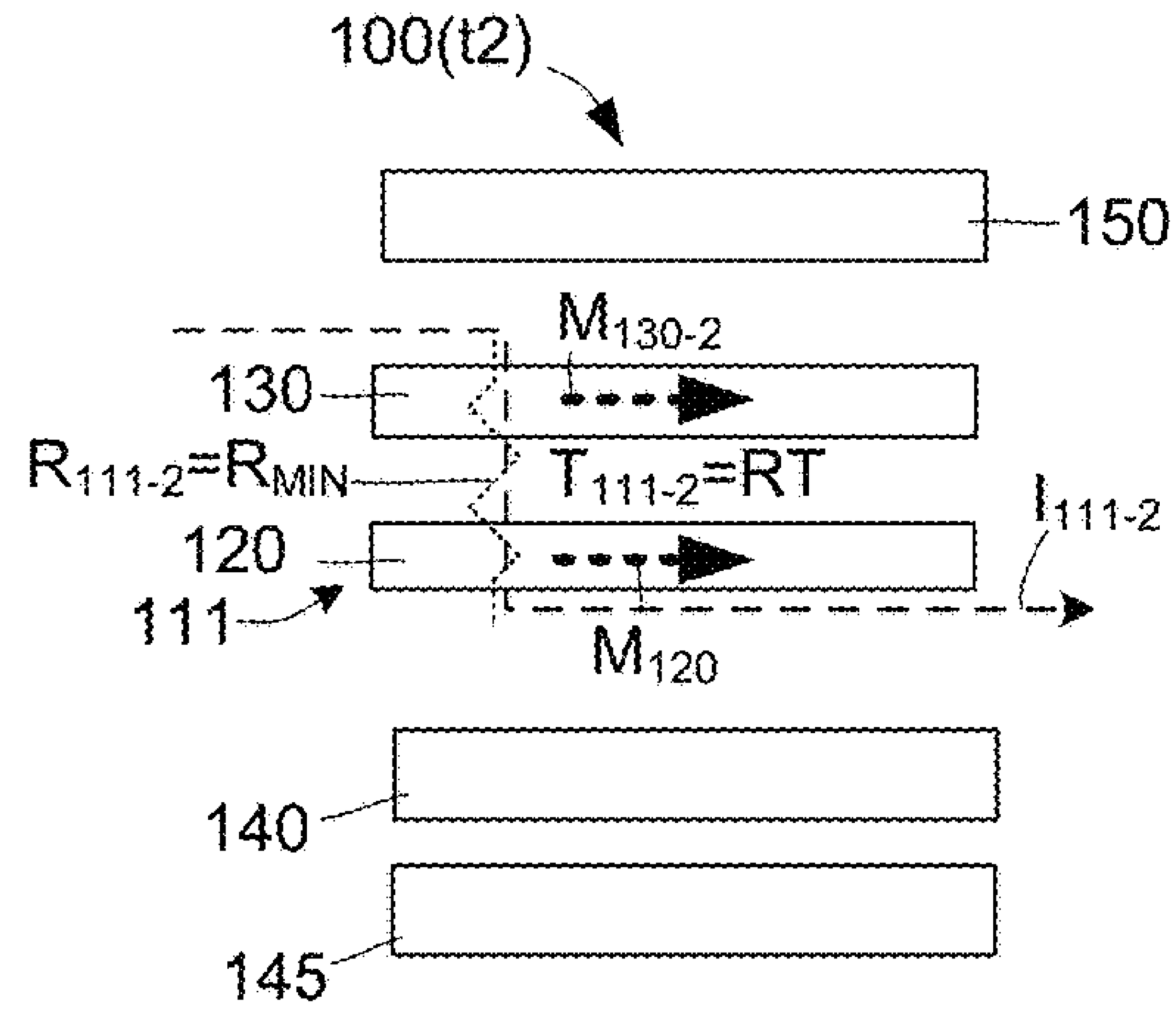

FIG. 3(B)

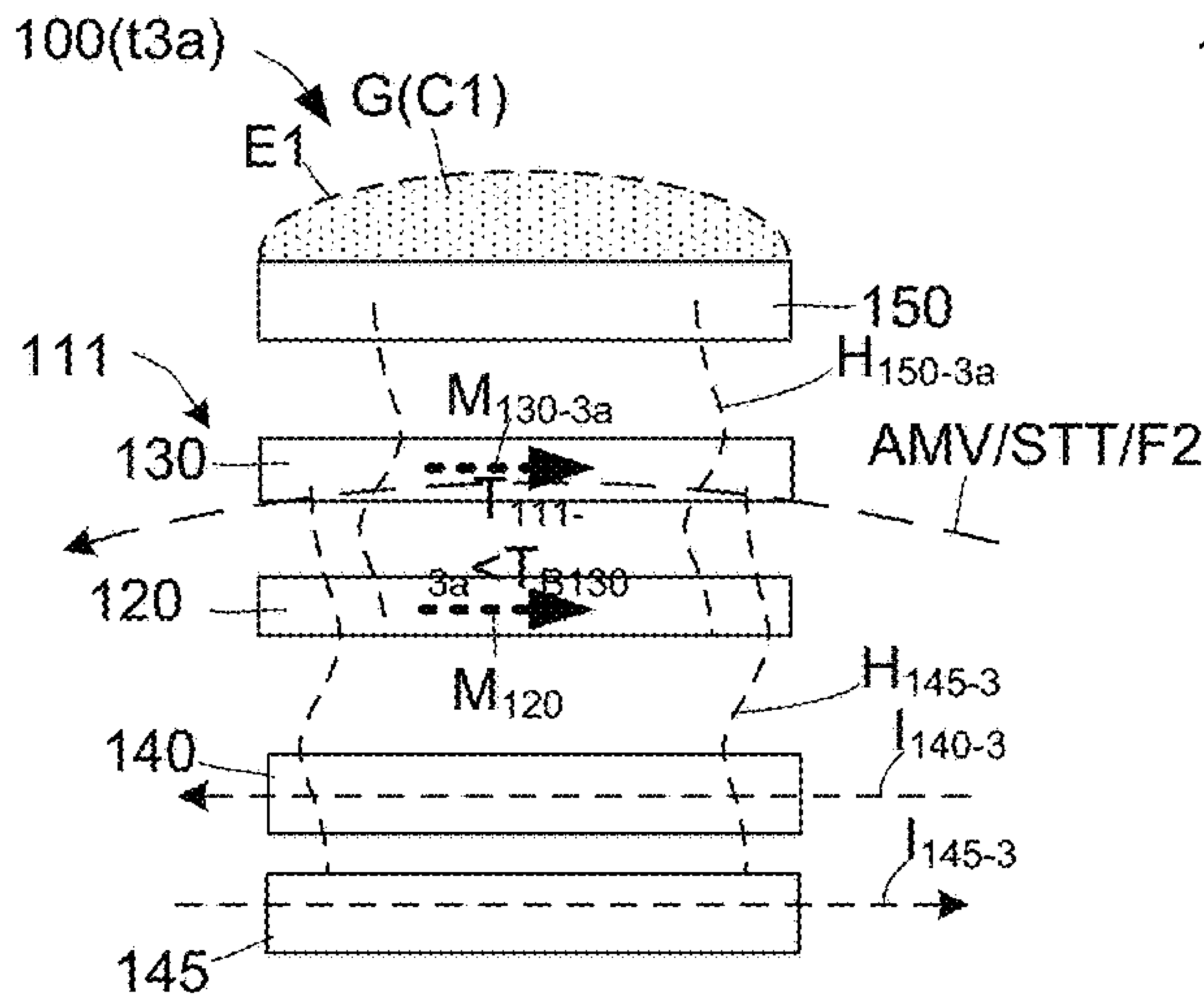

FIG. 3(C)

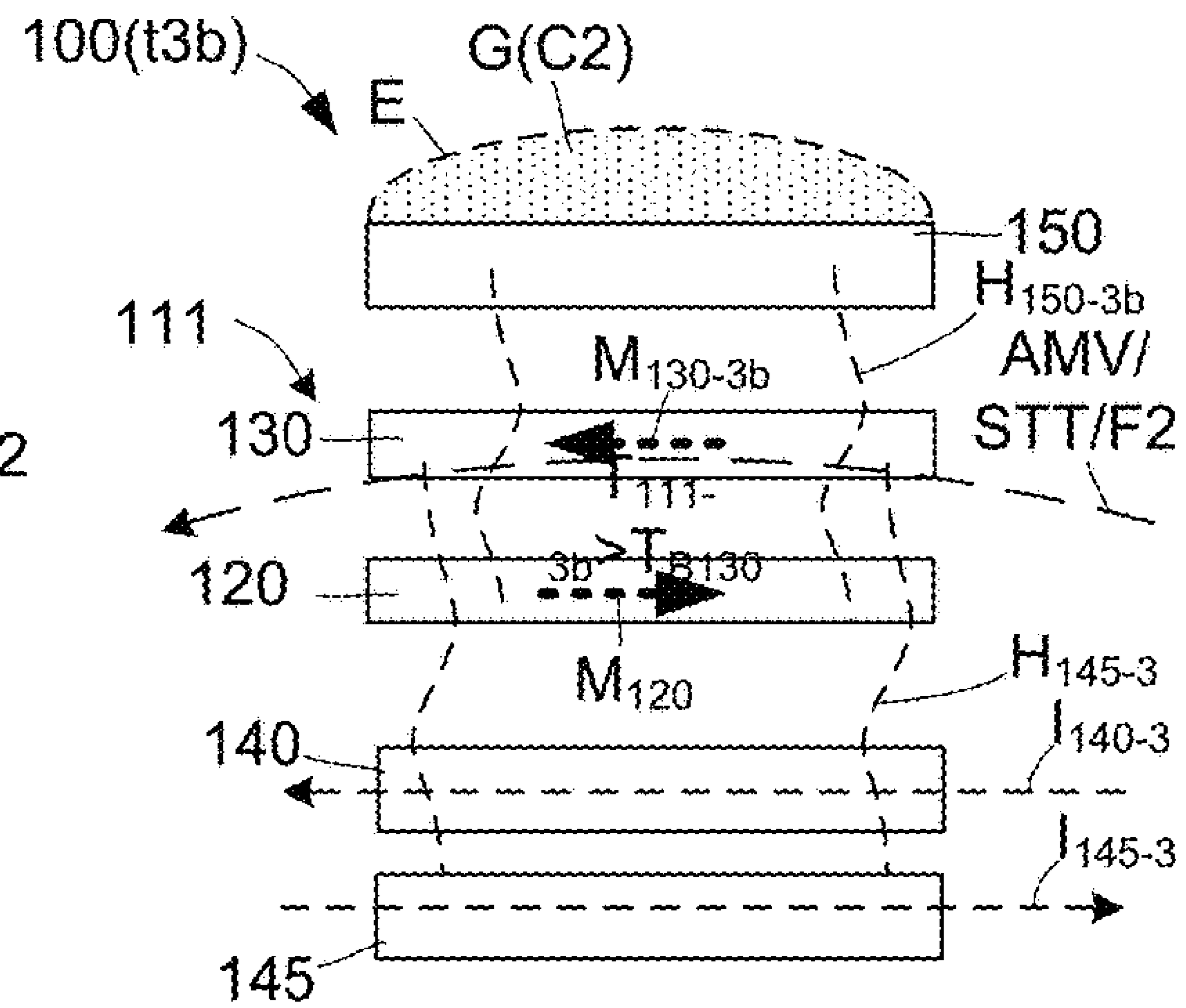

FIG. 3(D)

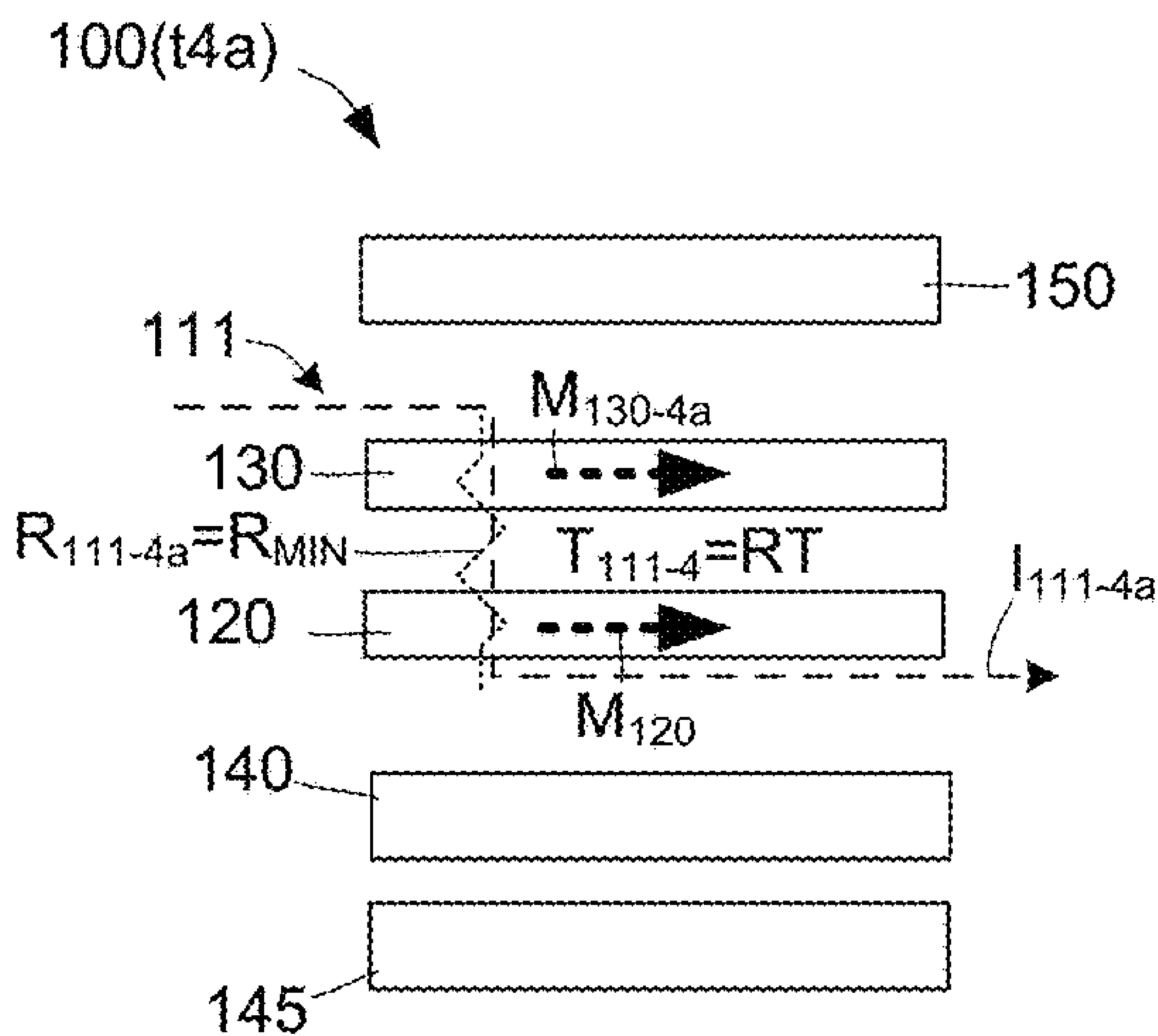

FIG. 3(E)

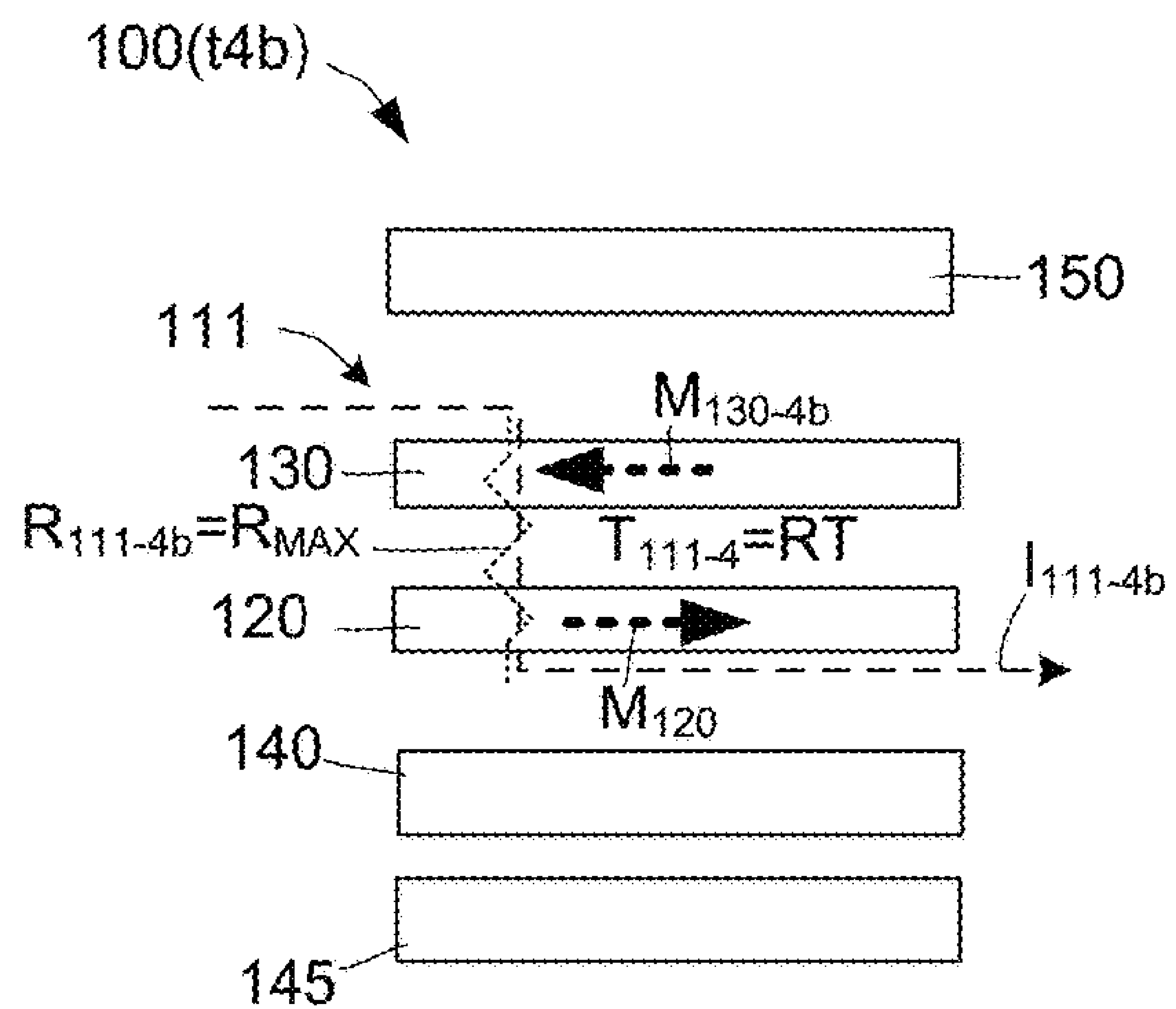

FIG. 3(F)

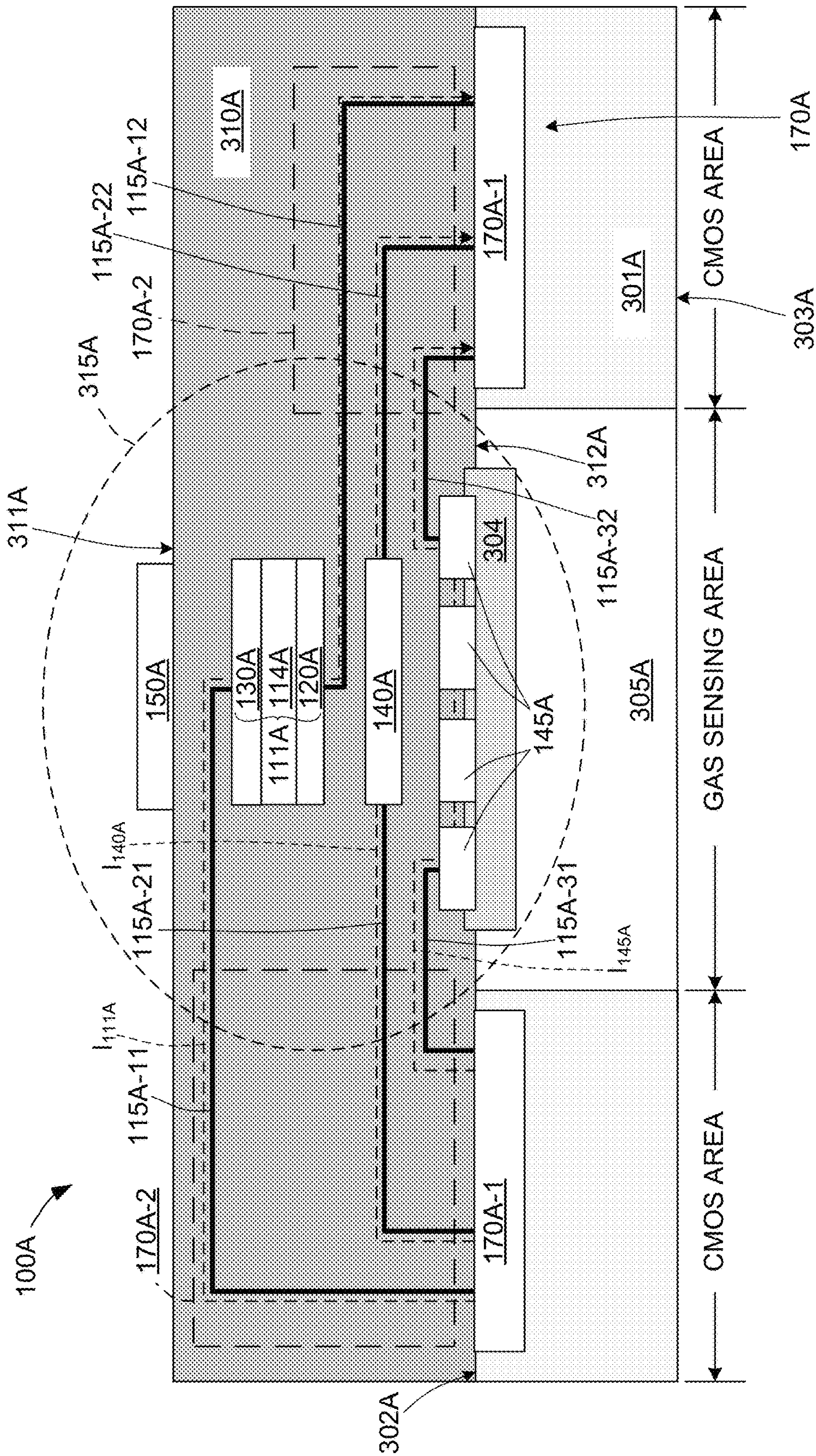

FIG. 4

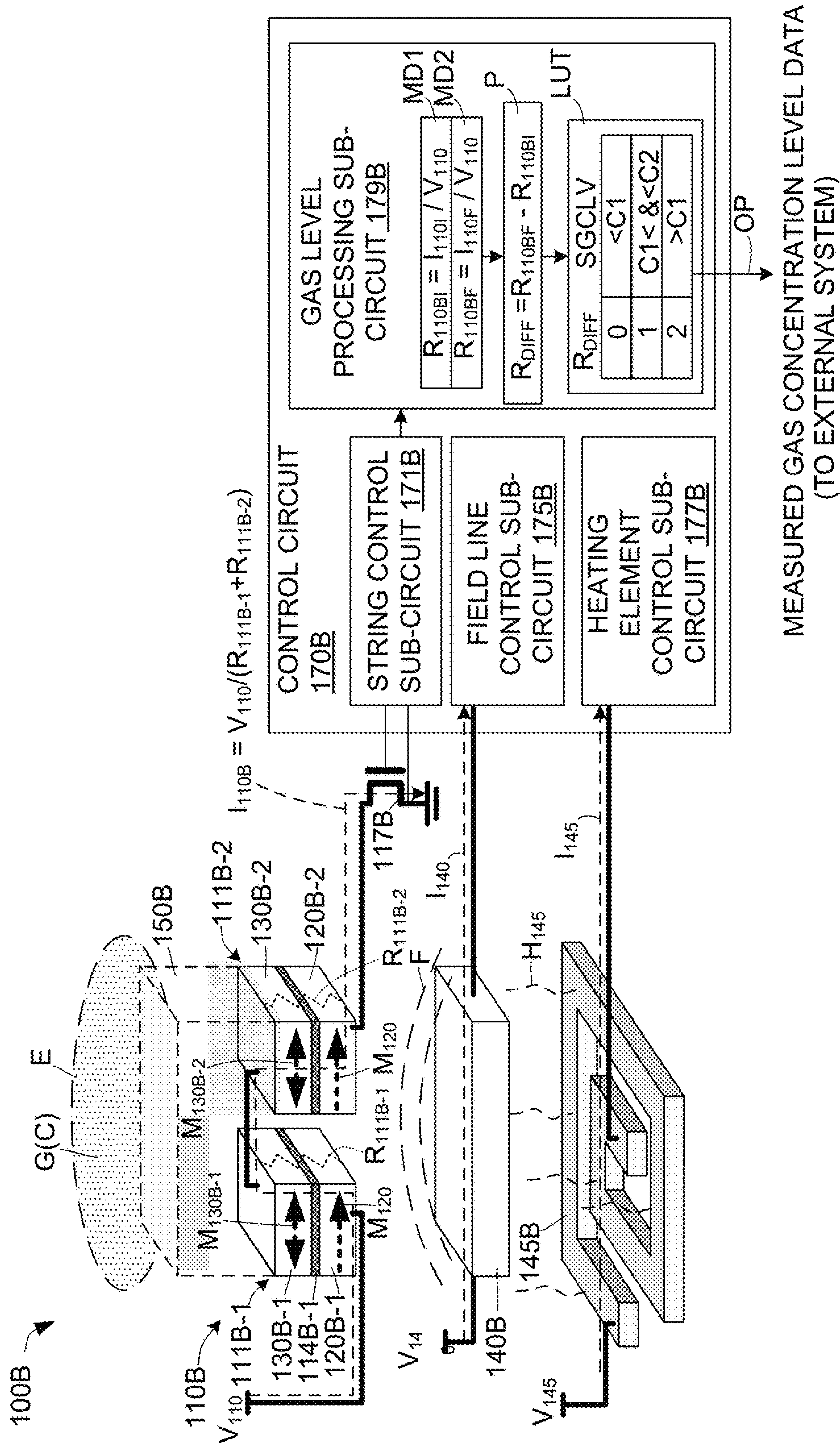

FIG. 5

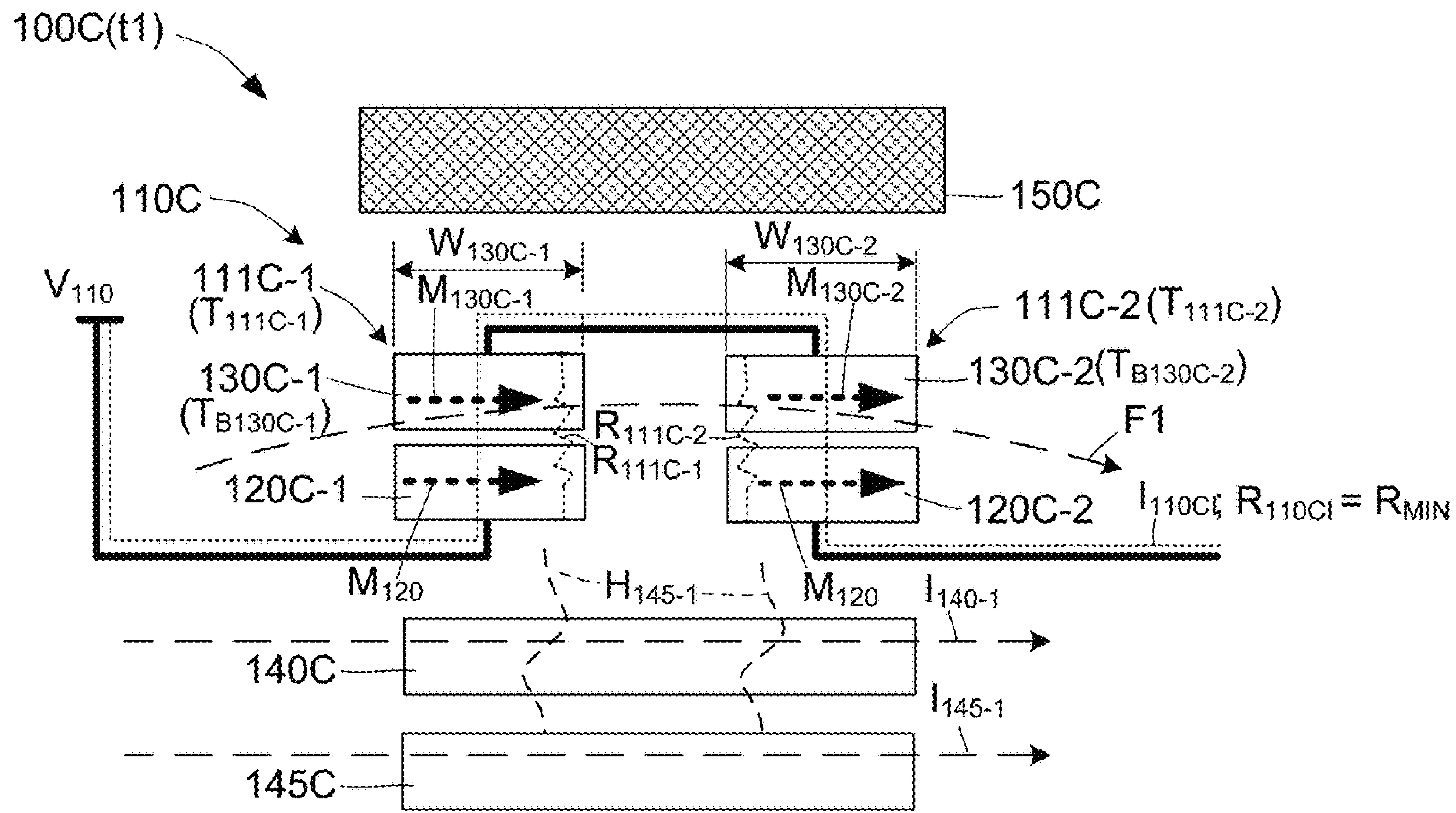

FIG. 6

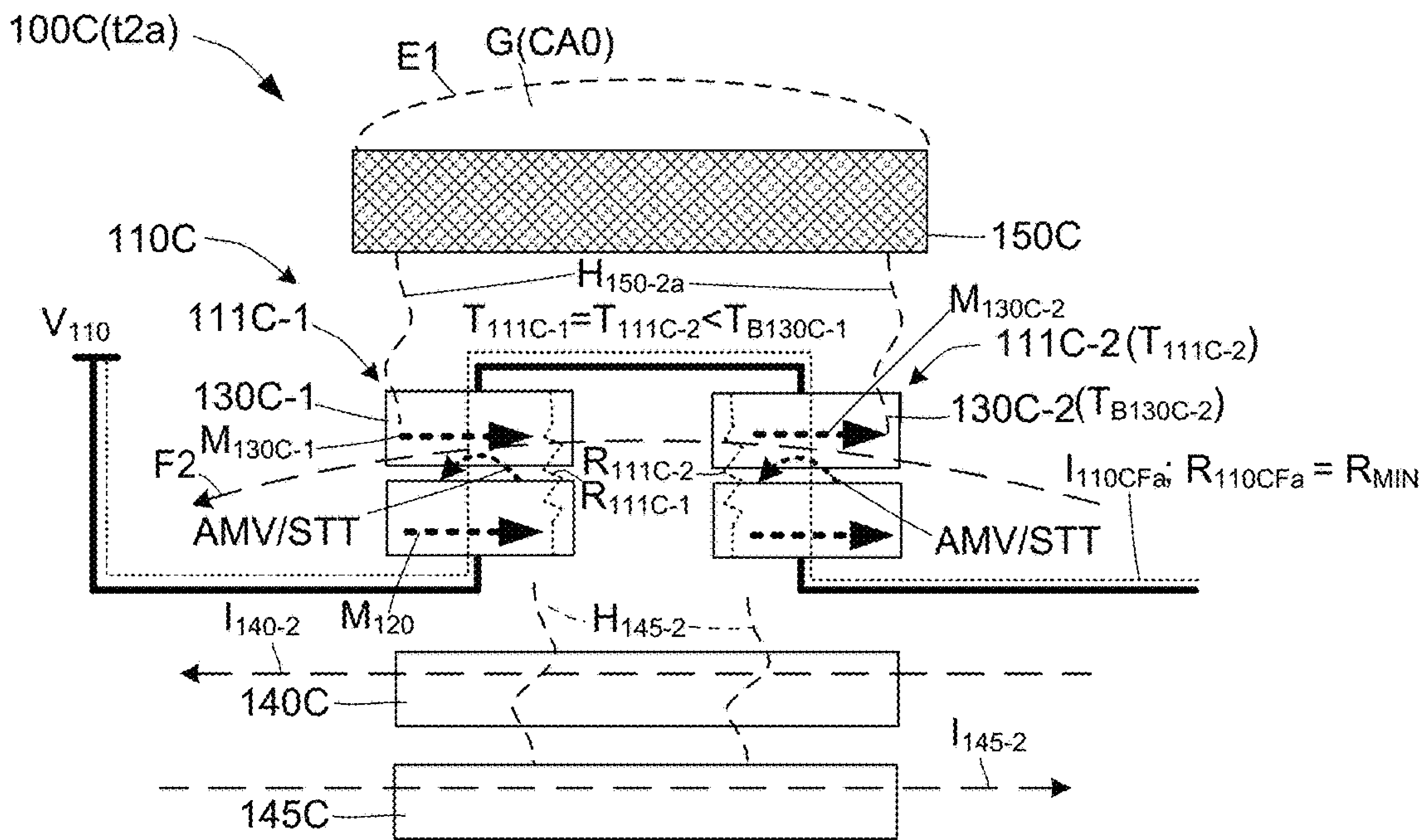

FIG. 7(A)

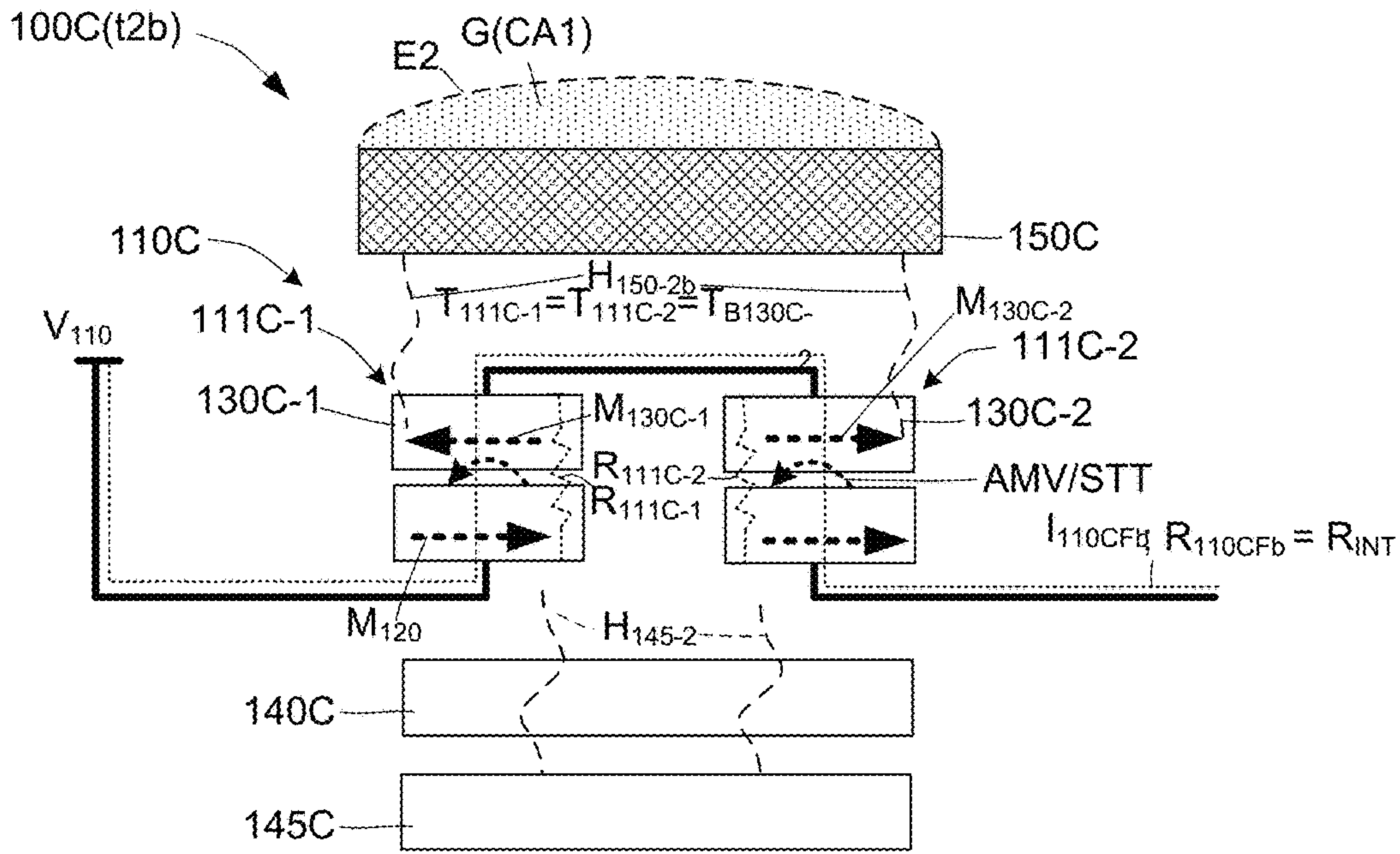

FIG. 7(B)

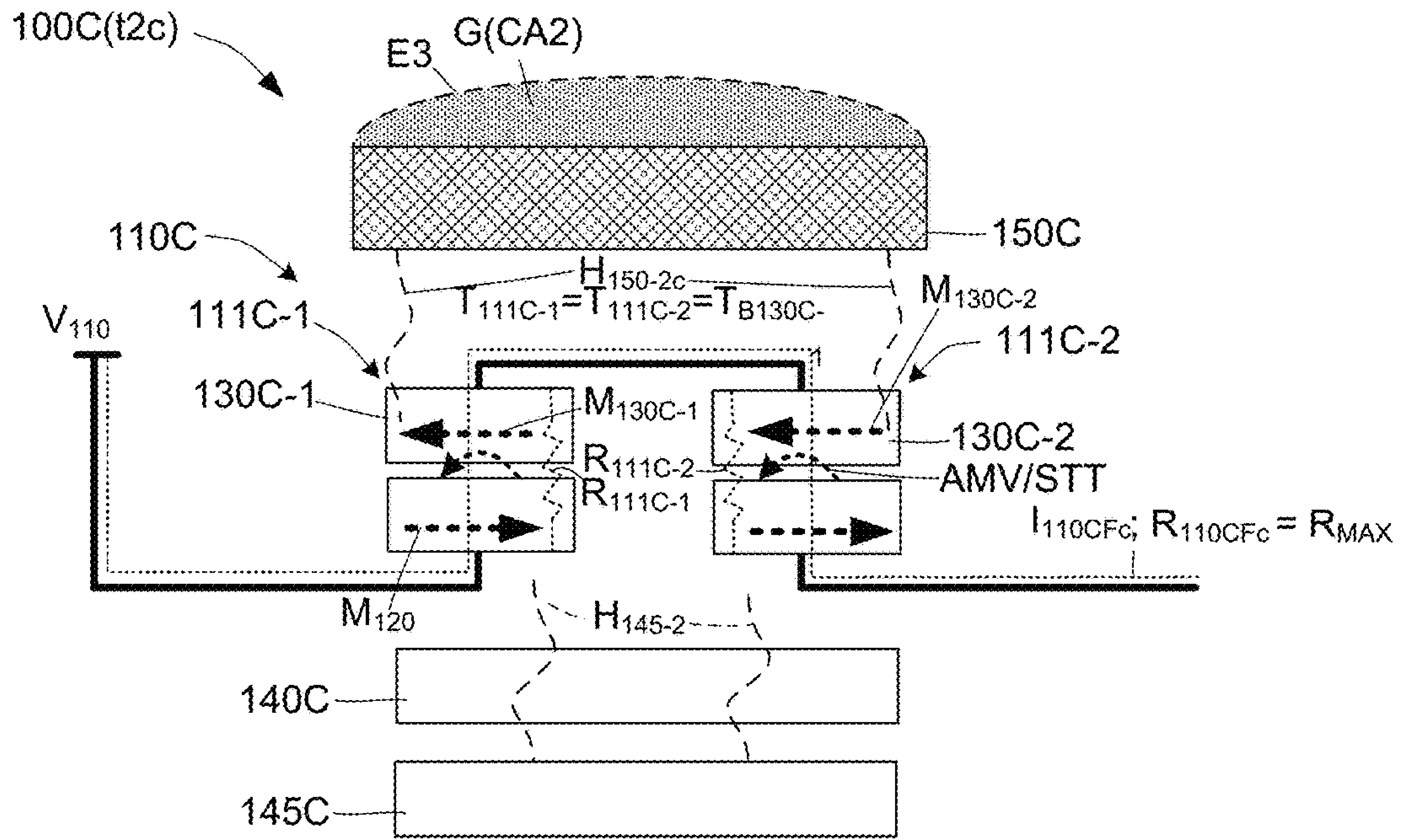

FIG. 7(C)

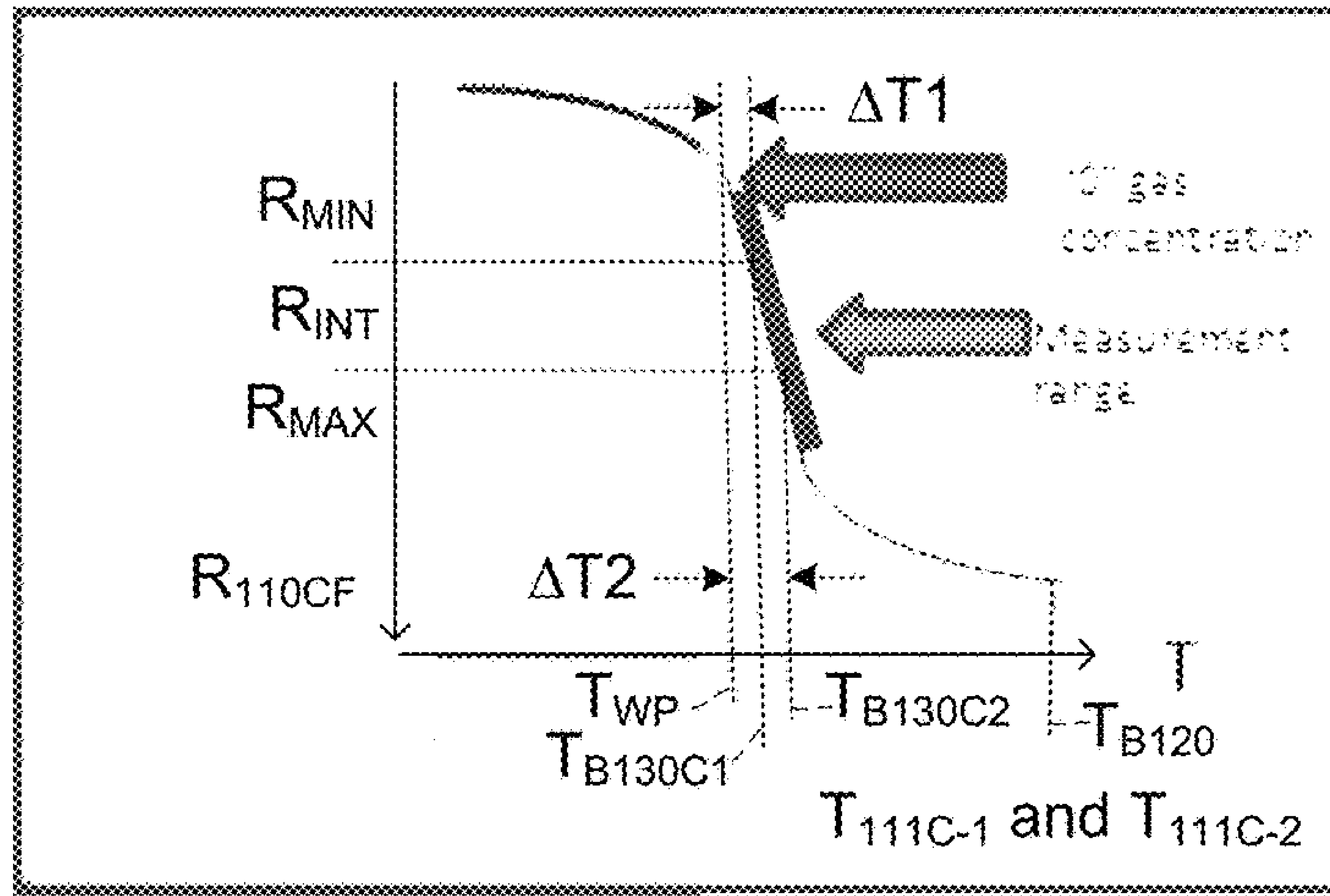

FIG. 8

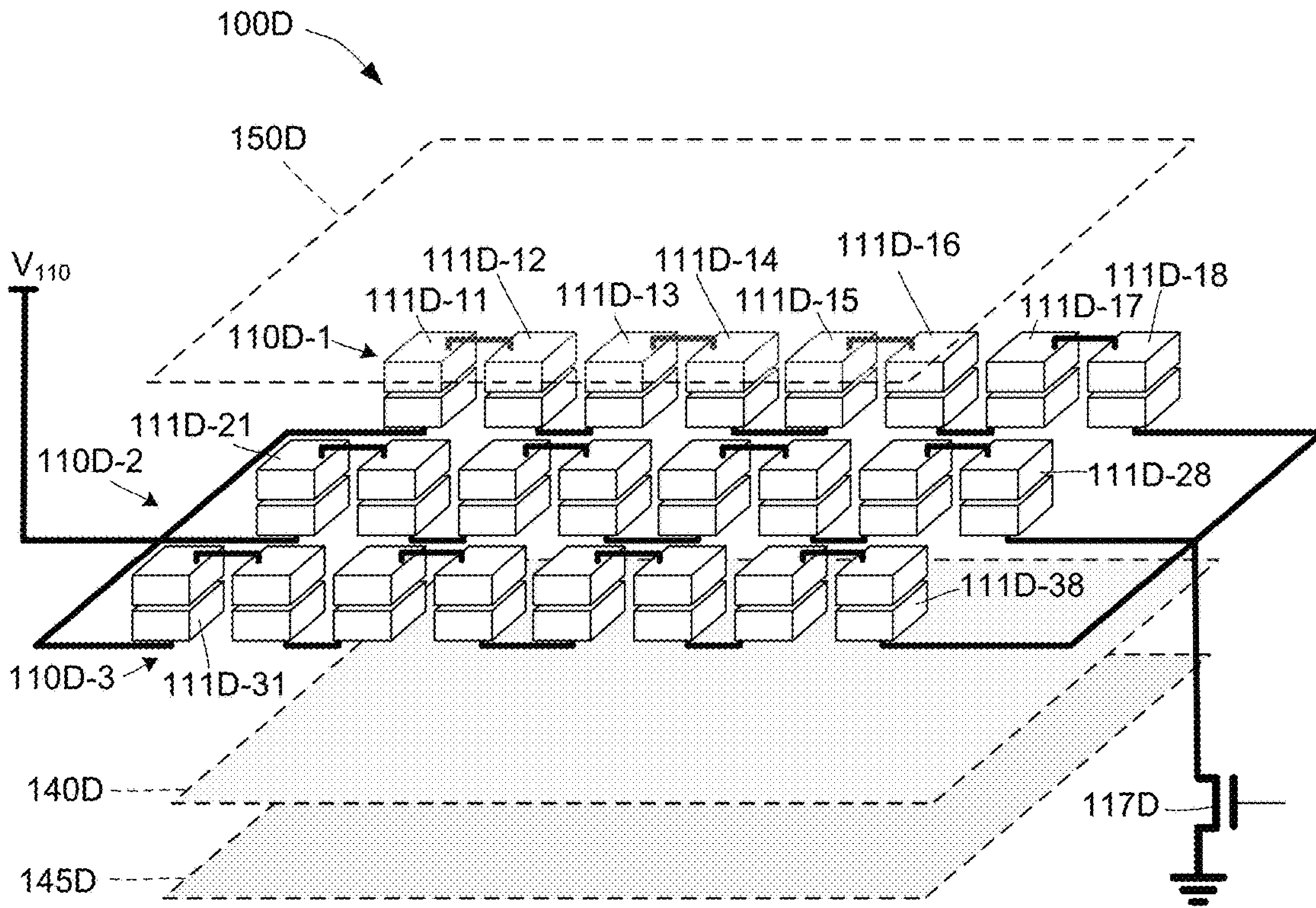

FIG. 9

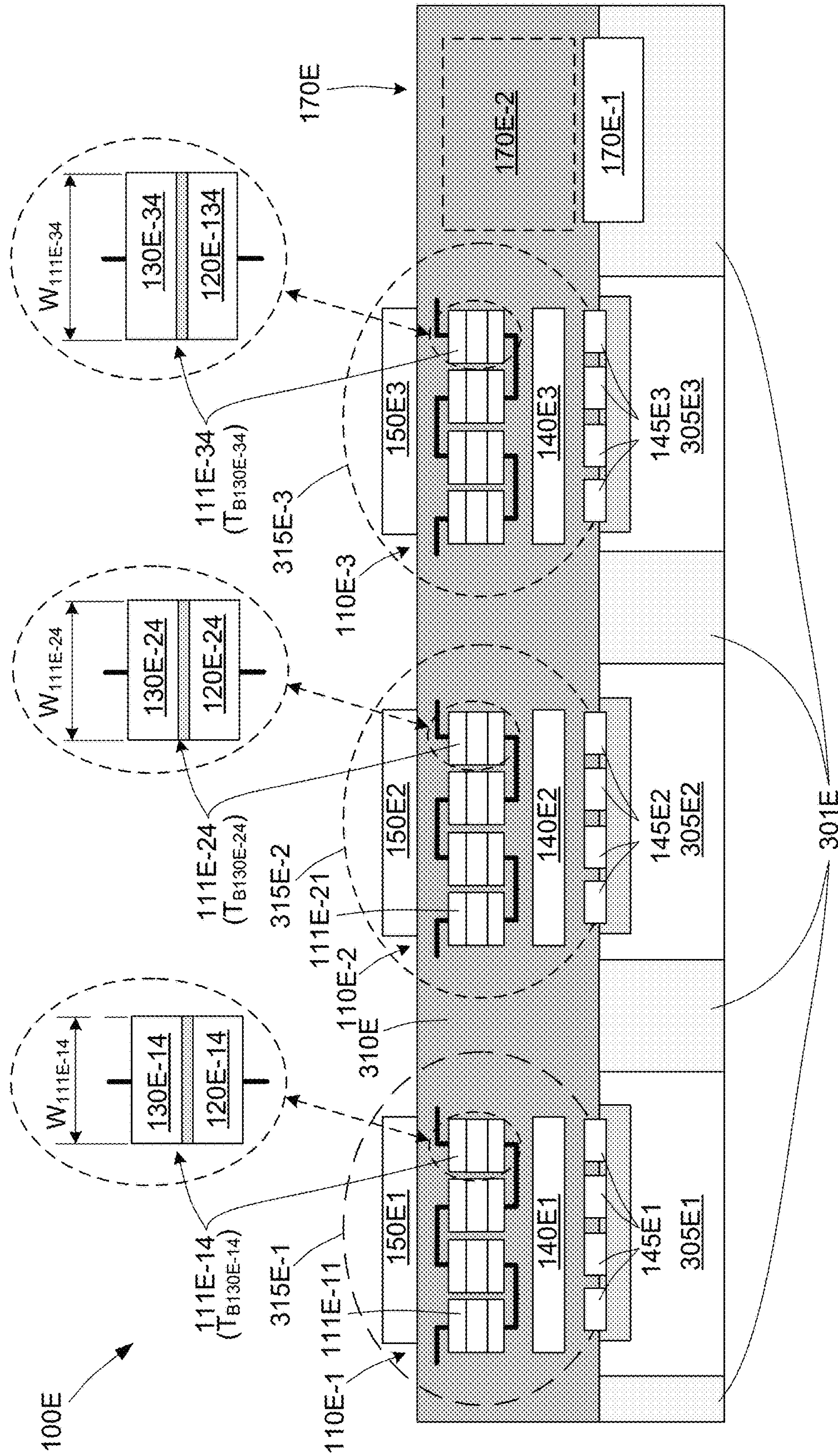

FIG. 10

GAS SENSING USING MAGNETIC TUNNEL JUNCTION ELEMENTS

FIELD OF THE INVENTION

This invention generally relates to sensors capable of detecting a target gas in an environment, and more particularly to gas sensing methods implemented by semiconductor gas sensors capable of determining concentration levels of a target gas.

BACKGROUND OF THE INVENTION

A gas sensor (aka, gas detector) is a device configured to detect the presence or absence of one or more target gases in a gaseous environment (e.g., a volume of air). For example, gas sensors are used to detect dangerous (e.g., flammable or toxic) gases in amounts that exceed minimum safety levels, or to detect oxygen depletion (i.e., when ambient oxygen levels fall below a predetermined concentration level). Gas sensors typically interface with a safety control system that performs a safety function in response to a positive detection signal generated by a gas sensor (e.g., to automatically shut down a process, or to sound a safety alarm, when the amount of target gas exceeds or falls below a predetermined concentration level).

Gas sensors capable of quantitatively measuring the concentration level of a target gas generally include remote-type gas sensors and contact-type gas sensors. Remote-type IR sensors, which include infrared (IR) point sensors and IR imaging sensors, are capable of detecting a target gas in a specified environment (i.e., the gas-filled volume containing the gas) without being in physical contact with the target environment, and are typically used to detect or measure gas leaks in large area environments such as oil refineries. However, remote-type gas sensors are typically expensive to produce and operate, and are thus impractical for detecting target gasses in smaller enclosed areas. In contrast to remote-type gas sensors, contact-type gas sensors are placed in direct contact with a monitored environment, and utilize gas sensing elements that react in a measurable way when a target gas is present in the environment. Contact-type gas sensors are typically smaller and less expensive than remote-type gas sensors, and are utilized mainly in enclosed areas such as buildings or processing chambers.

Semiconductor gas sensors are contact-type sensors including gas sensing elements whose electrical resistance changes in response to a reaction caused by the presence of a target gas, whereby detection or measurement of the target gas is achievable by way of monitoring changes in a current passed through the gas sensing element. The resistance change of gas sensing elements in semiconductor gas sensors is typically caused by one of three different reaction types: (i) a chemical reaction caused by changes in the composition or chemical structure of the gas sensing element in response to adsorption of the target gas into the gas sensing element; (ii) a temperature change of the gas sensing element as a result of endothermic or exothermic (e.g., combustion-type) reaction of the gas sensing element with the target gas; and (iii) a temperature change of the gas sensing element caused by a different thermal conductivity of the target gas versus ambient gases (this effect is dependent on gas flow over the sensing element). In both chemical-reaction-type gas sensors (i.e., semiconductor gas sensors configured in accordance with reaction type (i)) and in thermal-reaction-type gas sensors (i.e., semiconductor gas sensors configured in accordance with reaction types (ii) and

(iii)), the resulting change in electrical resistance across the gas sensing element is measurable by way of passing a current through the gas sensing element, and monitoring the current for changes that are characteristic of reactions with the target gas.

Semiconductor gas sensors have an advantage over other gas sensor types is that they can typically be produced using low-cost photolithographic fabrication processes developed for integrated circuit (IC) fabrication, and are therefore smaller and less expensive than other gas sensor types. In many cases, semiconductor gas sensors utilize bulk Si or SOI wafers as starting materials, and include a thermally isolated membrane formed by removing silicon from the rear of the wafer by plasma or wet etching. The etch stops at the BOX of the SOI or at silicon nitride layer formed at the surface of bulk silicon. The gas sensing element, sensors and a resistive heater are typically formed on the membrane, and control circuitry of the gas sensor is typically fabricated on the adjacent bulk Si or SOI using known semiconductor processing techniques. Typical semiconductor gas sensor designs include close-membrane sensors and membranes suspended by holding arms, with the gas sensing element typically disposed in a center of the membrane to improve thermal isolation.

A problem with conventional chemical-reaction-type semiconductor gas sensors is that they require gas sensing elements that are limited to detecting one or a relatively small number of target gases. That is, the detection mechanism of chemical-reaction-type semiconductor gas sensors requires adsorption of the target gas into the gas sensing element material, and there is no gas sensing element material that is receptive to all gas types. Therefore, chemical-reaction-type semiconductor gas sensors are either limited to one target gas (or a very small number of target gasses), or must include multiple gas sensor units, each unit having a different gas sensing element materials, in order to detect more than one target gas type.

Two chemical-reaction-type semiconductor gas sensors have been proposed in which the gas sensing element is incorporated into a magnetic tunnel junction (MTJ) element. MTJ elements typically include two ferromagnetic electrodes separated by a thin insulating layer and configured such that a resistance across the MTJ element depends on the relative orientations of the easy axes of magnetization (herein "magnetic orientations" or "magnetic directions") of the two ferromagnetic electrodes. The magnetic orientation of one of the ferroelectric electrodes is typically fixed (e.g., using an adjacent antiferromagnetic layer) and acts as a reference layer of the MTJ element, while the second ferromagnetic electrode forms a "free" layer of the MTJ element whose magnetic orientation can be switched by an external magnetic field between parallel and anti-parallel magnetic orientations relative to the reference layer. When the magnetic orientations of the reference and free layers are parallel, a current conductance through the tunnel dielectric is relatively high (i.e., the MTJ element is in a low resistance state), and when the magnetization vectors are anti-parallel, the current conductance is low (i.e., the MTJ element is in a high resistance state). A first MTJ-type chemical-reaction-type semiconductor gas sensor was disclosed in U.S. Pat. No. 8,826,726 (University of California, 2014), where the free layer of a modified MTJ element was formed with a gas adsorbing magnetic material (cobalt) that was found to cause the magnetic orientation of the free layer to flip from anti-parallel (out-of-plane) to parallel (in-plane) when sufficient amount of a gas to be detected (hydrogen) gas was adsorbed, and where the modified MTJ element could be

reset by heating the MTJ element to desorb the gas (i.e., heat is not used during the gas sensing phase). U.S. Pat. No. 9,097,677 (Univ. of Florida, 2015) discloses a second MTJ-based chemical-reaction-type semiconductor gas sensor in which two ferromagnetic structures are separated by a gas-sensitive metallic interlayer (e.g., palladium) such that a magnetic exchange coupling between the two ferromagnetic structures is affected by the amount of hydrogen gas adsorbed into the metallic interlayer. Similar to other chemical-reaction-type semiconductor gas sensors, MTJ-based chemical-reaction-type semiconductor gas sensors are limited in that they can only detect a limited number of gas types. Moreover, quantitative gas measurement using conventional MTJ-based chemical-reaction-type semiconductor gas sensor relies either on determining the time required for a single MTJ element to flip magnetic orientations, or determining magnetization vector angle changes when the temperature is switched from T**1** to T**2** value, with neither approach providing practical and sufficiently accurate quantitative measurement result data. Further, both U.S. Pat. Nos. 8,826,726 and 9,097,677 fail to specify cooling the MTJ elements to room temperature before measuring resistance in order to determine changes to the MTJ element's magnetic orientation.

Although not limited to a small number of target gasses like chemical-reaction-type semiconductor gas sensors, conventional thermal-reaction-type semiconductor gas sensors are insufficiently accurate in that they require measuring resistance changes at high temperatures. For example, combustion-type semiconductor gas sensors utilize catalyst-type gas sensing elements (e.g., Platinum or Palladium) that are heated to the threshold temperature of a combustible target gas, whereby the target gas exothermically reacts (oxidizes) to further increase the temperature of the catalyst-type gas sensing element to a reaction temperature, which is typically in the range of 100-350° C. Different target gasses have different threshold temperatures, so the catalyst-type gas sensing element is heated to different threshold temperatures at different times to detect different target gasses. Sensing of the reaction temperature increase is performed either by measuring current changes through the gas sensing element materials themselves (e.g., measuring resistance of a platinum catalyst), or by measuring the resistance of a sensor structure formed on the membrane adjacent to the gas sensing element (e.g., a specially formed MOSFET as taught, e.g., in D. Briand et al, IEEE EDL-22(I), pp. 11-13, 2001). Of these options, the special MOSFET approach currently provides the highest sensitivity (i.e., about 2%/° K at room temperature), with most other resistive sensor approaches exhibiting less than 0.5%/° K (IEEE Trans. ED vol. 52, 2005 "Temperature Sensitivity of SOI-CMOS Transistors for use in Uncooled Thermal Sensing", Eran Socher at al). However, in either case, the resistance measurement must take place during the exothermic reaction, which means that the measuring current must be passed through a measuring element (e.g., the special MOSFET or gas sensing element) that is close to the reaction temperature. Unfortunately, operation of the special MOSFET sensing transistor at high temperatures (above 150° C.) is limited due to leakage currents (even for partially or fully depleted SOI MOS transistors, where leakages are significantly lower than for the bulk devices). Moreover, the thermal sensitivity of the gas sensor's control circuit is strongly decreased at elevated temperatures (e.g., the thermal sensitivity of 0.35 μm transistors was observed as decreasing by approximately 50% at 100° C. as compared to room temperature).

What is needed is a method for operating a thermal-reaction-type semiconductor gas sensor that avoids the high-temperature resistance measurement problems associated with conventional thermal-reaction-type semiconductor gas sensors. What is also needed method for quickly and accurately determining the concentration level of a target (sensed) gas in a gaseous environment.

SUMMARY OF THE INVENTION

The present invention is directed to improved gas sensing methods that utilize one or more magnetic tunnel junction (MTJ) elements and one or more associated gas sensing elements in accordance with various novel operating strategies that avoid the high-temperature resistance measurement problems associated with conventional thermal-reaction-type semiconductor gas sensors, and/or facilitate substantially faster and more accurate concentration level measurements of one or more target gases in a gaseous environment using gas sensing elements of either the thermal-reaction type or the chemical-reaction type. Each of the novel operating strategies, which are set forth in exemplary embodiments described below, implements a core methodology in which each MTJ element is operably coupled to a gas sensing element and controlled during a gas sensing phase such that a resistance state of the MTJ element switches from a known initial (e.g., low) resistance value to an opposite (e.g., high) resistance value when the gas sensing element is exposed to target gas above a predetermined minimum concentration level, whereby each MTJ element is effectively utilized as a non-volatile memory cell that captures one bit of target gas concentration level data (i.e., either above or below the predetermined minimum concentration level) such that the data can be read out during a subsequent readout phase (i.e., by way of determining whether or not the resistance state of the MTJ element switched during the gas sensing phase). As set forth below with reference to exemplary embodiments, this core methodology is modified in accordance with various novel approaches to provide gas sensing methods that avoid the high-temperature resistance measurement problems associated with conventional thermal-reaction-type semiconductor gas sensors, and/or facilitate substantially faster and more accurate concentration level measurements of one or more target gases in a gaseous environment. Although the various novel approaches are described below with reference to associated exemplary embodiments that illustrate how the individual novel approaches provide improved gas sensing methods, it is understood that two or more of the novel approaches can be combined to provide gas sensing methods that represent a substantial improvement over conventional gas sensing approaches.

According to a first novel approach, the core methodology mentioned above is modified to facilitate thermal-reaction-type gas sensing applications in which the one or more MTJ elements are utilized to capture target gas concentration level data at high reaction temperatures for later readout at lower (e.g., room) temperatures, thereby avoid the high-temperature resistance measurement problems associated with conventional thermal-reaction-type semiconductor gas sensors. The first novel approach utilizes a thermal-reaction-type gas sensing element that is configured to generate reaction heat in an amount proportional to a currently measured target gas concentration level, and is operably thermally coupled to the MTJ element(s) such that reaction heat generated by the gas sensing element at least partially contributes to each MTJ element's temperature. In accor-

dance with an aspect of the first novel approach, each MTJ element is configured such that a storage blocking temperature of the MTJ element's storage layer is within a normal operating temperature range of the thermal-reaction-type gas sensor (i.e., with the high end of the operating range defined by the reaction heat generated by the thermal-reaction-type gas sensing element), whereby the storage magnetic orientation of the storage layer is made switchable during normal operation of the gas sensor between two directions (i.e., whenever the MTJ element's temperature is above the storage blocking temperature). In addition, the MTJ element is further configured such that a reference magnetic orientation of the MTJ element's reference layer remains permanently fixed in one direction during normal operation of the gas sensor, whereby the storage magnetic orientation is switchable between a parallel direction and an anti-parallel direction relative to the reference magnetic orientation. Consistent with conventional MTJ elements, each MTJ element's resistance state has a low resistance value when the storage magnetic orientation is parallel to the reference magnetic orientation, and has a high resistance value when the storage magnetic orientation is anti-parallel to the reference magnetic orientation. As such, when subjected to a magnetic biasing force having a direction opposite to its current magnetic direction, each MTJ element's resistance state is caused to switch from a first (e.g., low) resistance value to a second (e.g., high) resistance value when the MTJ element's temperature is increased above its storage blocking temperature, and becomes fixed in the second (e.g., high) resistance value when the MTJ element's temperature subsequently decreases below the storage blocking temperature, whereby the switched/non-switched state can be determined by applying a fixed voltage across the MTJ element at a low (e.g., room) temperature, and measuring the resulting read current passing through the MTJ element in order to determine the post-gas-sensing resistance state. Accordingly, by correlating the reaction heat generated by the gas sensing element with the storage blocking temperature of each MTJ element such that the MTJ element's temperature increases above its storage blocking temperature when the gas sensing element is exposed to target gas above a predetermined minimum concentration level, the first novel approach facilitates thermal-reaction-type gas sensing applications in which MTJ elements are utilized to capture target gas concentration level data at high reaction temperatures for later readout at lower (e.g., room) temperatures, thereby avoiding the high-temperature resistance measurement problems associated with conventional thermal-reaction-type semiconductor gas sensors.

According to a first exemplary embodiment utilizing the first novel approach mentioned above, in order to cause the MTJ element's resistance state to reliably switch (e.g., from low to high) resistance values when the gas sensor is exposed to target gas above the predetermined minimum concentration level, the MTJ element's resistance state is initialized (fixed) in a first (e.g., low) resistance state during a reset phase by way of temporarily increasing the MTJ's temperature above the MTJ element's storage blocking temperature while applying an initial (first) magnetic bias force (e.g., by way of generating an external magnetic field directed in a first direction), and then, during a subsequent gas sensing phase, subjecting the MTJ element an opposing magnetic biasing force (e.g., an anti-parallel alignment of magnetization vectors (AMV) force, spin torque transfer and/or an external magnetic field directed opposite to the first direction) while receiving reaction heat from the gas sensing element. In an exemplary embodiment, the reset phase involves generating a first amount of control heat (e.g., by way of activating a resistive heating element) such that the MTJ temperature increases above the storage blocking temperature, generating an initial external magnetic bias field such that storage magnetic orientation is biased into in the desired parallel direction relative to the reference magnetic orientation, and then decreasing the MTJ temperature below the storage blocking temperature (e.g., by de-activating the heating element or otherwise acting to cool the MTJ element), whereby the storage magnetic orientation becomes fixed in the initial (parallel) direction. Note that the initial external magnetic bias field is maintained during the cooling process, but may be terminated after the MTJ temperature falls below the storage blocking temperature. To facilitate CDS readout operations, an initial resistance value of the MTJ element is determined at the end of the reset process, preferably after the MTJ element has cooled to room temperature, for example, by coupling the MTJ element to a read voltage source and measuring the resulting read current passing through the MTJ element.

Once the MTJ element's resistance state is initialized (fixed) in the first (e.g., low) resistance state during the reset phase, the presence of target gas above (i.e., equal to or greater than) the predetermined minimum concentration level is reliably detected by way of increasing the MTJ element's temperature to and maintaining the MTJ element's temperature at a work point temperature, which is below the storage blocking temperature, while a (second/opposing) magnetic bias force is applied to the MTJ element. In one embodiment, the work point temperature generally coincides with the lowest temperature at which reaction heat is generated by a gas sensing element in response to the target gas, and the temperature difference between the work point temperature and the MTJ element's storage blocking temperature corresponds to the predetermined minimum gas concentration level at which the target gas causes the MTJ element to switch resistance states. That is, the gas sensor is configured such that any reaction heat generated by the gas sensing element increases the MTJ element's temperature above the work point temperature. Target gas concentrations below the predetermined minimum gas concentration level produce reaction heat in a relatively low amount that fails to increase the MTJ element's temperature above the MTJ element's storage blocking temperature, and therefore fails to cause a change in the MTJ element's resistance state. Conversely, when the gas sensing element is exposed to target gas at or above the predetermined minimum concentration level, gas sensing element generates reaction heat in an amount sufficient to increase the MTJ element's temperature from the work point temperature to a temperature above (i.e., equal to or greater than) the MTJ element's storage blocking temperature. In one embodiment, maintaining the MTJ temperature at or above the work point temperature involves generating a corresponding (second) amount of control heat (e.g., using the gas sensor's heating element). In this case, when a currently measured gas concentration level of the target gas is above the predetermined minimum gas concentration level, a corresponding amount of reaction heat generated by the gas sensing element combines with the corresponding (second) amount of control heat to increase the MTJ element's temperature above its storage blocking temperature, whereby the second magnetic bias force (e.g., the AMV force or spin torque transfer mentioned above, an external magnetic field having a direction opposite to the initial direction, or a combination of two or more of these forces)

biases storage magnetic orientation into the anti-parallel (second) direction relative to the reference magnetic orientation, whereby the resistance state of the MTJ element switches from the initial low resistance value to a high resistance value. The presence of target gas above the predetermined minimum gas concentration level is thus determined, for example, by way of identifying (e.g., by re-coupling the MTJ element to the read voltage source, measuring the resulting read current, and comparing the measured read current with the read current that was measured at the end of the reset phase) that a final resistance state of the MTJ element had switched during the gas sensing phase. Of course, if the final resistance state had not switched, the initial and final resistance states would be the same. In either case, measured gas concentration level data indicating the switched/non-switched state is generated indicating that target gas was either blow or above the predetermined minimum gas concentration level.

According to a second novel approach, a thermal-reaction-type semiconductor gas sensor includes multiple MTJ elements of the type described above that are operably thermally coupled to one or more thermal-reaction-type gas sensing elements, where each of the MTJ elements is configured with a different storage blocking temperature, thereby providing "higher resolution" gas concentration measurements than is achievable using a single MTJ element. That is, when two MTJ elements are produced with two different storage blocking temperatures (i.e., either by way of fabrication techniques or because of inherent blocking temperature variances), when operably thermally coupled to receive reaction heat from a thermal-reaction-type gas sensing elements such the MTJ temperatures of the two MTJ elements increase at the same rate, each of the two MTJ elements is caused to switch its resistance state in response to a different gas concentration level. For example, in a hypothetical two-element gas sensor arrangement in which the storage blocking temperature of a first MTJ element is lower than the storage blocking temperature of the second MTJ element, only the first MTJ element switches when the gas sensing element generates a relatively low amount of reaction heat in response to a relatively low gas concentration level that increases the MTJ temperatures of both MTJ elements to the lower storage blocking temperature, and both MTJ elements switch when the gas sensing element generates a relatively high amount of reaction heat in response to a relatively high gas concentration level that increases the MTJ temperatures of both MTJ elements from a work point temperature to a temperature equal to or greater than the higher storage blocking temperature. In this two-MTJ example, the final resistance states of the two MTJ elements provides quantitative measured gas concentration level data indicating whether the measured gas concentration is in a range below lower concentration level (indicated by neither MTJ element switching its resistance state), in a range between the lower and higher concentration levels (indicated by switching of the first MTJ element and non-switching of the second MTJ element), or in a range above the higher concentration level (indicated by both MTJ elements switching their resistance states). By applying this multiple-MTJ sensor approach to gas sensors including more than two MTJ elements, each configured to switch its resistance state at a different gas concentration level, one skilled in the art can easily recognize that this arrangement can be used to quantitatively measure gas concentration levels with a high degree of accuracy (i.e., "high resolution") by way detecting very small gas concentration level differences. For example, a gas sensor would provide high resolution quantitative gas measurement by including multiple MTJ elements that are respectively configured to switch at equally-spaced different blocking temperatures distributed over a given temperature range (e.g., at intervals of 5° C. over a range of 120° C. to 145° C., i.e., such that a first MTJ element has a storage blocking temperature of 120° C., a second MTJ element has a storage blocking temperature of 125° C., etc.).

According to an aspect of the second novel approach, a single (shared) field line is utilized to simultaneously control all of the MTJ elements, thereby providing a simplified control methodology that is scalable to any number of MTJ elements. Similar to the first approach described above, the field line structure is utilized to generate one or more external magnetic fields that serve as a magnetic bias force during a gas sensor's operating cycle (e.g., during the reset phase and/or during the gas sensing phase). In accordance with the second novel approach, the shared field line structure is operably magnetically coupled to all of the multiple MTJ elements, and is configured such that the external magnetic field generated by the shared field line structure simultaneously substantially equally biases the storage magnetic orientations of all of the multiple MTJ elements in a single direction defined by the external magnetic field. In a preferred embodiment, the shared field line arrangement is utilized during the reset phase to fix the storage magnetic orientations of all associated MTJ elements in the parallel magnetic direction (i.e., in their low resistance state), whereby the MTJ elements are configured such that AMV force can be utilized as an applied magnetic bias force during the subsequent gas sensing phase to cause each MTJ element to switch to the high resistance state when its MTJ temperature is equal to or exceeds its associated storage blocking temperature. By fixing all of the multiple MTJ elements in the low resistance state at reset, the process of determining the switched/non-switched state of the MTJ elements during the subsequent gas sensing phase is thus greatly simplified in that no field line or MTJ currents are required during the gas sensing phase. Moreover, because all of the MTJ elements are reset into the same direction, a single (shared) field line (and associated control circuitry) can be used to reset all of the MTJ elements, no matter how many MTJ elements are used.

Various alternatives to the second novel approach are described with reference to associated specific embodiments. For example, in one case a heating element is utilized to generate control heat in the manner described above in order to facilitate reset and gas sensing operations of the thermal-reaction-type gas sensor. In addition, although utilizing spin torque transfer to generate switching during the gas sensing phase facilitates low power operations and is therefore presently preferred, in an alternative possible embodiment the shared field line arrangement may be utilized during the gas sensing phase to generate an opposite external magnetic field (e.g., by way of reversing the field line current direction), whereby the storage magnetic orientations of all associated MTJ elements are reliably biased into the anti-parallel magnetic direction (i.e., into their high resistance state). In another exemplary embodiment, the multiple MTJ elements are series-connected to simplify readout operations by facilitating determining the resistance states of all of MTJ elements using a single read current (i.e., instead of separate read currents passed through each MTJ element individually).

According to a third novel approach, semiconductor gas sensors are utilized that include multiple MTJ elements and an associated gas sensor similar to those described above

(i.e., wherein the gas sensor is configured such that each MTJ element switches its resistance state in response to a different gas concentration level), wherein the multiple MTJ elements are coupled in a way that forms a NAND-type series-connected string such that a total string resistance of the series-connected string is collectively defined by (e.g., the sum of) the corresponding individual MTJ resistance values of the MTJ elements. In addition to providing quantitative gas concentration level measurements by way of utilizing multiple MTJ elements that switch resistance states at different gas concentration levels (as explained above), the NAND-type series-connected string arrangement further simplifies the gas sensing operation by way facilitating the use of a single read current to determine the resistance state of all of the series connected MTJ elements. That is, by initializing all of the MTJ elements during the reset phase to a common (e.g., low) resistance state, and controlling the gas sensing operation such that the MTJ elements switch to the opposite (e.g., high) resistance state in accordance with an associated gas concentration level, the number of MTJ elements that switched state during a given gas sensing phase can be determined by calculating the difference between a measured final string resistance and a stored initial string resistance value, where zero difference would mean no MTJ elements switched states (indicated little or no target gas), and a maximum possible difference would mean all of the MTJ elements switched states (indicating a high target gas concentration level). Further, gas sensors implementing the NAND-type series-connected string arrangement are readily scalable to provide a range of measurement accuracies, for example, by way of increasing the number of MTJ elements in each series-connected string or connecting multiple series-connected strings in parallel, and/or by configuring each MTJ element of a series connected string to switch its resistance state at a slightly different gas concentration level (e.g., by way of forming different MTJ elements with different lateral sizes), thereby providing gas sensors capable of measuring very small gas concentration level variations.

According to an aspect of the third novel approach, gas concentration level measurement is conducted in accordance with correlated double sampling (CDS) techniques by way of determining an initial resistance value of each NAND-type series-connected string at the end of the reset phase, conducting a gas sensing phase in the manner described above, determining a final resistance value of the series-connected string after the gas sensing phase is completed, and then utilizing a difference between the initial resistance value and the final resistance value to generate measured gas concentration level data. The application of CDS readout techniques to gas measurement is believed to be novel in that it is not believed to be utilized in any commercially implemented gas sensing methodologies. In this case, the implementation of CDS readout is made possible because each MTJ element's initial and final resistance states are stably fixed (i.e., stored in a non-volatile manner), and the accuracy provided by CDS readout facilitates the use of a large number of MTJ elements in each series-connected string, which is turn facilitates highly accurate quantitative gas measurements in a very short amount of time (i.e., highly accurate quantitative gas measurement data is generated using a single gas sensor operating cycle). Moreover, in the specific case of thermal-reaction-type gas sensors, the CDS readout approach provides an additional benefit in that the stably fixed (non-volatile) data stored on the MTJ elements can be readout after the MTJ elements have cooled to a low (e.g., room temperature), whereby thermal-reaction-type gas sensors implementing the NAND-type series-connected string arrangement achieve substantially higher readout accuracies in comparison to conventional thermal-reaction-type gas sensors that require measuring currents/resistances using MOSFETs during the gas sensing phase at high temperatures. That is, performing of both read current measurements at room temperature represents a key distinction of the present invention over all prior art gas sensing approaches because this approach avoids high leakage currents and noise (i.e., due to resistance fluctuations connected with the fluctuations of temperature) that limit the accuracy of conventional gas sensing methodologies, and the use of CDS techniques even further increases the accuracy of the measurement results. Although these and other benefits of utilizing the NAND-type string and CDS readout approach are significantly greater when applied to thermal-reaction-type gas sensors, other semiconductor gas sensor types (e.g., chemical-reaction-type gas sensors) may be produced that would also benefit from the NAND-type string and CDS readout approach. Therefore, unless otherwise specified, the combined series-connected string and CDS readout of the third novel approach is intended to apply to either chemical-reaction-type or thermal-reaction-type gas sensors unless thermal-reaction-type sensing elements are specified in the appended claims.

Various alternatives to the third novel approach are described with reference to associated specific embodiments. For example, heating elements and field lines are utilized in accordance with techniques described above to facilitate room temperature readout operations and to facilitate reliable switching. In another exemplary embodiment, measured gas concentration level data is generated by way of calculating (e.g., using a processor provided on the gas sensor device) a difference between the initial and final string resistance values, and the utilizing the calculated difference to access a corresponding gas concentration level data stored on the gas sensor device (e.g., in a look-up table), and then transmitting the accessed corresponding gas concentration level data through an output port of the gas sensor device for use in an external system.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features, aspects and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings, where:

FIG. **1** is a simplified perspective view showing a semiconductor gas sensor including an MTJ element according to an embodiment of the present invention;

FIG. **2** is flow diagram showing an exemplary operating cycle performed by the gas sensor of FIG. **1** according to another embodiment of the present invention;

FIGS. **3**(A), **3**(B), **3**(C), **3**(D), **3**(E) and **3**(F) are simplified side views showing the gas sensor of FIG. **1** during various operating phases of the operating cycle shown in FIG. **2**;

FIG. **4** is a simplified cross-sectional side view showing a membrane-type semiconductor gas sensor forming using CMOS fabrication techniques according to an exemplary embodiment of the present invention;

FIG. **5** is a simplified perspective view showing a semiconductor gas sensor including multiple MTJ elements according to another exemplary embodiment of the present invention;

FIG. **6** is a simplified side views showing a thermal-reaction-type gas sensor including multiple MTJ elements according to another exemplary embodiment of the present invention;

FIGS. **7**(A), **7**(B) and **7**(C) are simplified side views showing the gas sensor of FIG. **6** during different gas sensing phases;

FIG. **8** is resistance versus temperature graph illustrating operating principles of the thermal-reaction-type gas sensor of FIG. **6**;

FIG. **9** is simplified diagram showing multiple MTJ element strings connected in parallel according to another embodiment of the present invention; and

FIG. **10** is a simplified cross-sectional side view showing a semiconductor gas sensor including multiple string-based membrane-type sensor regions according to an exemplary embodiment of the present invention.

DETAILED DESCRIPTION OF THE DRAWINGS

The present invention relates to an improvement in methods utilized to detect and measure selected target gases in an environment. The following description is presented to enable one of ordinary skill in the art to make and use the invention as provided in the context of a particular application and its requirements. As used herein, directional terms such as "upper" and "lower" are intended to provide relative positions for purposes of description, and are not intended to designate an absolute frame of reference. In addition, the terms "coupled" and "connected", which are utilized herein, are defined as follows. The term "connected" is used to describe a direct connection between two circuit elements, for example, by way of a metal line formed in accordance with normal integrated circuit fabrication techniques. In contrast, the term "coupled" is used to describe either a direct connection or an indirect connection between two circuit elements. For example, two coupled elements may be directly connected by way of a metal line, or indirectly connected by way of an intervening circuit element (e.g., a capacitor, resistor, inductor, or by way of the source/drain terminals of a transistor). Various modifications to the preferred embodiment will be apparent to those with skill in the art, and the general principles defined herein may be applied to other embodiments. Therefore, the present invention is not intended to be limited to the particular embodiments shown and described, but is to be accorded the widest scope consistent with the principles and novel features herein disclosed.

FIG. **1** shows a thermal-reaction-type gas sensor **100** for detecting a target gas G in an environment E according to a first exemplary embodiment of the present invention. Gas sensor **100** includes a magnetic tunnel junction (MTJ) element **111** that is operably thermally coupled to a gas sensing element **150** such that an MTJ temperature T_{111} of MTJ element **111** is at least partially influenced by reaction heat H_{150} generated by gas sensing element **150**. Although not shown in FIG. **1**, it is understood that an intervening structure (e.g., a layer of dielectric material) is disposed between gas sensing element **150** and MTJ element **111**.

MTJ element **111** generally includes a reference layer **120** and a storage layer **130** separated by a tunnel dielectric layer **114**. Reference layer **120** includes a magnetic structure that defines a reference magnetic orientation M_{120}, and storage layer **130** includes a second magnetic structure that defines a storage magnetic orientation M_{130}. According to an aspect of the present invention, reference layer **120** is configured as a high-coercivity magnetic structure such that reference magnetic orientation M_{120} remains fixed in a single magnetic direction during normal operation of gas sensor **100**, and storage layer **130** is configured as a low-coercivity magnetic structure such that storage magnetic orientation M_{130} is switchable (changeable) between two magnetic directions during normal operation of gas sensor **100**, whereby a resistance state R_{111} of MTJ element **111** is changeable (switchable) between two (i.e., relatively low and relatively high) resistance values. In the exemplary embodiment, reference layer **120** is configured such that reference magnetic direction M_{120} remains fixed in first magnetic direction MD_0, which is depicted using right-pointing arrow in FIG. **1**, and storage layer **130** is configured such that storage magnetic orientation M_{130} is switchable between first magnetic direction MD_0 and second magnetic direction MD_1, which is depicted using left-pointing arrow in FIG. **1** (i.e., opposite to magnetic direction MD_0). The magnetic orientations of reference layer **120** and storage layer **130** are "parallel" when storage magnetic orientation M_{130} is fixed in the same direction as reference magnetic direction M_{120} (e.g., both storage magnetic orientation M_{130} and reference magnetic direction M_{120} are aligned in first magnetic direction MD_0). Conversely, the magnetic orientations of reference layer **120** and storage layer **130** are "anti-parallel" when storage magnetic orientation M_{130} is fixed in an opposite direction to that of reference magnetic direction M_{120} (e.g., storage magnetic orientation M_{130} is fixed in second magnetic direction MD_1 and reference magnetic direction M_{120} is fixed in first magnetic direction MD_0). A current resistance state R_{111} of MTJ element **111** is correlated to the parallel/non-parallel directions in that resistance state R_{111} has a low resistance value when storage magnetic orientation M_{130} is parallel to reference magnetic orientation M_{120}, and has a high resistance value when storage magnetic orientation M_{130} is anti-parallel/opposite to reference magnetic orientation M_{120}. For reference, typical resistances of high and low states for an MTJ having a diameter of 200 nm and MgO thickness of 12-14 A are 2 kOhm and 700 Ohm to 1 kOhm, respectively, which corresponds to a tunnel magneto-resistance ratio (TMR) of approximately 100% to 200%. Accordingly, the parallel/antiparallel orientation of storage layer **130** relative to reference layer **120** at a given point in time can be easily determined by way of determining resistance state R_{111} of MTJ element **111** at that time.

According to an aspect of the first exemplary embodiment, storage magnetic orientation M_{130} is made switchable between parallel and anti-parallel directions relative to reference magnetic orientation M_{120} by way of configuring storage layer **130** such that its associated storage blocking temperature T_{B130} that is within the normal operating temperature range experienced by MTJ element **111** (i.e., the temperature range of MTJ temperature T_{111}), and by way of configuring reference layer **120** such that it has an associated reference blocking temperature T_{B120} that is higher than the normal operating temperature range experienced by MTJ element **111**. The normal operating temperature range of MTJ temperature T_{111} is established by temperatures generated on gas sensor **100** under normal operating conditions, whereby MTJ temperature T_{111} of MTJ element **111** normally varies between a minimum temperature (e.g., room temperature, approximately 24° C.) and a maximum temperature (e.g., approximately 250° C.). In one embodiment, storage layer **130** is a multi-layer structure including an antiferromagnetic (AF) structure **132** and a ferromagnetic structure **135** disposed in close proximity such that an exchange interaction between the two structures produces

storage magnetic direction M_{130}, and the desired switchability of storage magnetic orientation M_{120} at normal operating temperatures of gas sensor **100** is achieved by way of fabricating AF structure **132** using an AF material having an associated storage blocking temperature T_{B130} that is within the expected normal operating temperature range of MTJ temperature T_{111}. That is, when a temperature of AF structure **132** is below its associated storage blocking temperature T_{B130}, it becomes highly resistant to switching its magnetic direction in response to an external magnetic bias force, whereby storage magnetic direction M_{130} becomes "fixed" (i.e., pinned or unchangeable) in one of two directions (e.g., MD_0 or MD_1). Conversely, when the temperature of AF structure **132** is above its associated storage blocking temperature T_{B130}, AF structure **132** becomes less resistant to change, whereby storage magnetic orientation M_{130} is switchable between directions MD_0 and MD_1 by applied magnetic bias forces (e.g., external magnetic fields). With storage layer **130** configured in this way, storage magnetic orientation M_{130} is switchable during operation of gas sensor **100** whenever MTJ temperature T_{111} increases above storage blocking temperature T_{B130}. In contrast, reference layer **120** is fabricated using a different AF structure **122** disposed in contact with an associated ferromagnetic structure **125**, where AF structure **122** is fabricated using an AF material having an associated storage blocking temperature T_{B120} that is greater than the normal operating temperature range of MTJ element **111**, whereby reference magnetic orientation M_{120} remains permanently fixed (e.g., in first magnetic direction MD_0) because MTJ temperature T_{111} of MTJ element **111** does not increase above reference blocking temperature T_{B120} during normal operations of gas sensor **100**.

According to a presently preferred embodiment illustrated in FIG. **1**, MTJ element **111** is produced in a stack-type arrangement with (first) ferromagnetic structure **125** and (second) ferromagnetic structure **135** respectively disposed in contact with opposite (upper and lower) surfaces of tunnel dielectric layer **114**, and with (first) AF structure **122** and (second) AF structure **132** respectively disposed on respective opposite (upper and lower) surfaces of ferromagnetic structures **125** and **135**. In a specific exemplary embodiment, ferromagnetic layers **125** and **135** comprise one or more of Fe, Co, Ni and their alloys, such as, e.g., FeCo. According to an aspect of the preferred embodiment, reference AF structure **122** comprises a first AF material exhibiting associated reference blocking temperature T_{B120} and storage AF structure **132** comprises a second (different) AF material having associated storage blocking temperature T_{B130}, where the two different AF materials are selected such that the reference blocking temperature T_{B120} is substantially greater (higher) than the storage blocking temperature T_{B130}. More specifically, reference AF structure **122** comprises a first AF material having a reference blocking temperature T_{B120} that is preferably higher than the maximum expected operating temperature of gas sensor **100** (e.g., greater than approximately 250° C.), whereby reference magnetic orientation M_{120} remains effectively permanently fixed (e.g., in direction MD_0 indicated in FIG. **1**) after being initialized during fabrication. In contrast, storage AF structure **132** comprises an AF material having a storage blocking temperature T_{B130} that is approximately midway within the expected normal operating temperature range of gas sensor **100** (e.g., approximately 125° C.). In a specific exemplary embodiment, reference AF structure **122** comprises an AF material (e.g., one or more of PtMn or NiMn) having a reference blocking temperature T_{B120} in the range of 250-350° C., and storage AF structure **132** comprises an AF material (e.g., one or more of FeMn or IrMn) having a storage blocking temperature T_{B130} in the range of 120-250° C. In one embodiment, the AF material in each layer can be coupled to a synthetic AF structure comprising of two magnetic layers sandwiched with a thin ruthenium layer—such a synthetic AF structure has a very strong antiparallel coupling. If the ferromagnetic with AF pinning is coupled also to a synthetic AF structure, the coupling of the reference ferromagnetic layer over the storage ferromagnetic layer is small (synthetic AF structures produce small stray magnetic fields extending into the opposite electrode).

In an exemplary embodiment (referring to FIG. **1**), MTJ element **111** has an overall cell thickness L_{111} in the range of 50 to 200 nanometers, and has a nominal width/diameter W_{111} (i.e., maximum top view dimension) in the range of 50 to 500 nanometers, and more preferably in the range of 100 to 250 nanometers. Reference AF structure **122** is fabricated with a thickness L_{122} in the range of 10 and 30 nm, reference ferromagnetic structure **125** is fabricated with a thickness L_{125} in the range of 5 and 70 nm, tunnel dielectric layer **114** (e.g., magnesium oxide (MgO) or aluminum oxide (Al_2O_3)) is fabricated with a thicknesses L_{114} in the range of 10 to 20 Angstroms, storage ferromagnetic structure **135** is fabricated with a thickness L_{135} in the range of 5 and 70 nm, and storage AF structure **132** is fabricated with a thickness L_{132} in the range of 5 and 30 nm. Forming MTJ element **111** using these dimensions both minimize fabrication defects (e.g., shorts) and produces desirable resistance characteristics that facilitate the write/program and compare operations that are described below.

In one embodiment, MTJ element **111** is further configured such that an anti-parallel alignment of magnetization vectors (AMV) force or spin torque transfer STT (spin-polarized current) is directed from reference layer **120** into the free magnetic layer (storage layer **130**) with sufficient magnetic force to facilitate switching of storage magnetic orientation M_{130} during the operating cycle of gas sensor **100**. In the case of AMV, although magnetic fields typically do not extend outside each AFM/FM stack, it is possible to modify layer borders and grains of the AFM such that a magnetic field generated by reference layer **120** imposes a magnetic bias on storage layer **120** having sufficient strength to switch storage layer **120** from the parallel to the anti-parallel orientation. In the case of spin torque transfer (STT), an electrical current in the MTJ causes spin torque that is transferred by electrons moving from reference layer **120** to storage layer. Referring to FIG. **1**, both force AMV and spin torque STT are directed from reference layer **120** to storage layer **130**, where a magnetic moment (indicated by the double-headed dashed-line arrow in FIG. **1**) is transferred to storage layer **130** by the bias force or spin torque of electrons polarized by reference layer **120**. Both the AMV force and spin torque transfer result in bias forces similar to the repelling force experienced by two bar magnets placed in parallel with their North poles together—in the absence of a countering force, one of the magnets will rotate because a North-to-South pole alignment is the lower energy state. When the dimensions of MTJ element **111** are adjusted using known techniques to sufficiently enhance AMV, the resulting field provides a sufficiently strong magnetic bias force that can be used to bias storage magnetic orientation M_{130} into the anti-parallel direction relative to reference magnetic orientation M_{120} when MTJ temperature T_{111} is above storage blocking temperature T_{B130} (i.e., and below reference blocking temperature T_{B120}, and in the absence of a conflicting external magnetic biasing field). Specifically, when

storage magnetic orientation M_{130} and reference magnetic orientation M_{120} are in parallel directions (e.g., referring to FIG. **1**, both are fixed in first magnetic direction MD_0) and then MTJ temperature T_{111} is increased above storage blocking temperature T_{B130} (and no current is supplied to field line structure **140**), force AMV causes storage magnetic orientation M_{130} to switch to the anti-parallel (opposite) direction relative to reference magnetic orientation M_{120} (i.e., such that reference magnetic orientation M_{120} remains fixed in first magnetic direction MD_0, but storage magnetic orientation M**130** switches to second magnetic direction MD_1). Configuring MTJ element **110** to produce sufficient AMV force therefore provides an advantage over STT and field line force F**2** in that this arrangement facilitates reliably switching resistance state R_{111} of MTJ element **111** from the low resistance (parallel direction) value to the high resistance (anti-parallel direction) value without applying any current to gas sensor **100**, thereby facilitating low energy consumption operations.

Referring again to FIG. **1**, gas sensing element **150** is disposed on an external region of gas sensor **100** such that it physically contacts environment E (and, hence, target gas G, when present in environment E) during gas sensing operations, and is disposed relative to MTJ element **111** such that reaction heat H_{150} generated by gas sensing layer **150** significantly influences MTJ temperature T_{111} of MTJ element **111**. In one embodiment, gas sensing element **150** is separated from by a thin layer of passivation material (not shown), and is configured in a manner similar to thermal-reaction-type gas sensing elements used in conventional thermal-reaction-type gas sensors such that reaction heat H_{150} is generated by gas sensing element **150** in an amount proportion to an actual (currently measured) concentration level C of target gas G in environment E. In a presently preferred embodiment, gas sensing element **150** is a combustion-type gas sensing element in which reaction heat H_{150} is generated by combustion of target gas G that comes into contact with gas sensing element **150** in a manner consistent with conventional reaction type (ii), which is described in the background section above. In an alternative embodiment, gas sensing element **150** is implemented using reaction type (iii) in which reaction heat H_{150} is produced by way of thermal conductivity of target gas G passing over gas sensing element **150**.

According to another aspect of the first embodiment, gas sensor **100** is configured such that reaction heat H_{150} generated by gas sensing element **150** during a gas sensing phase increases MTJ temperature T_{111} of MTJ element **111** from a lower temperature above (i.e., equal to or greater than) storage blocking temperature T_{B130} only when currently measured concentration level C of target gas G in environment E is above (i.e., equal to or greater than) a predetermined minimum concentration level. That is, because the amount of reaction heat H_{150} generated by gas sensing element **150** is proportional to a given measured concentration level, because MTJ temperature T_{111} of MTJ element **111** is proportional to reaction heat H_{150} by way of the operable thermal coupling between gas sensing element **150** and MTJ element **111**, and because storage magnetic orientation M_{130} resists switching directions (i.e., from parallel to anti-parallel directions, or vice versa) unless MTJ temperature T_{111} is above storage blocking temperature T_{B130}, gas sensor **100** is configured to indicate whether a currently measured concentration level C of target gas G is above or below the predetermined minimum gas concentration level by way of the switched/non-switched state of storage layer **130** after the gas sensing phase. For example, when a given measured concentration level C of target gas G were below the predetermined minimum concentration level, the generated amount of reaction heat H_{150} would be insufficient to increase MTJ temperature T_{111} above storage blocking temperature T_{B130}, whereby switching of storage magnetic orientation M_{130} would not be possible, and gas sensor **100** would indicate that the given measured concentration level is below the predetermined minimum gas concentration level by way of the non-switched state of storage layer **130** after completion of the gas sensing phase. Conversely, when a given measured concentration level C of target gas G is above the predetermined minimum concentration level, the generated amount of reaction heat H_{150} increases MTJ temperature T_{111} above storage blocking temperature T_{B130}, whereby switching of storage magnetic orientation M_{130} is made possible (i.e., by way of an applied magnetic bias force, as described below), and gas sensor **100** indicates that the given measured concentration level is above the predetermined minimum gas concentration level by way of the resulting switched state of storage layer **130** after completion of the gas sensing phase. Thus, by configuring gas sensor **100** such that reaction heat H_{150} increases MTJ temperature T_{111} above storage blocking temperature T_{B130} only when currently measured concentration level C is above the predetermined minimum concentration level, the present invention facilitates detecting target gas G in concentration levels above the predetermined minimum gas concentration level by way of determining the switched/non-switched state of storage magnetic orientation M_{130} after a given gas sensing phase of the gas sensor's operating cycle.

According to an exemplary specific embodiment depicted in simplified form in FIG. **1**, the readout of resistance state R_{111} of MTJ element **111** is implemented by coupling MTJ element **111** between a read voltage source V_{111} and a ground terminal by way of a select transistor **117**, and controlling select transistor **117** by way of MTJ element measurement sub-circuit **171** during the readout phase (and, optionally, at the end of the reset phase) of each sensor operating cycle. More specifically, voltage source V_{111} is applied on a conductive line **115-11** (e.g., metallization line), which is coupled to storage AF layer **132** of MTJ element **111** by way of a metal via **116-1**, and reference AF layer **122** of MTJ element **111** is in turn connected by way of a metal via **116-2** and a conductive line **115-12** to ground by way of select transistor **117**. With this arrangement, determining resistance state R_{111} of MTJ element **111** is achieved by turning on select transistor **117** to generate a read current I_{111} from fixed voltage source V_{111} through MTJ element **111**, measuring the resulting read current I_{111} (e.g., using a current sensor **172**), and the determining the high/low resistance value of resistance state R_{111} by way of determining whether read current is relatively high (indicating resistance state R_{111} is low) or relatively low (indicating resistance state R_{111} is high).

Referring again to FIG. **1**, gas sensor **100** further includes an on-chip field line structure **140** that is physically spaced from MTJ element **111** by an intervening dielectric or insulating structure (not shown), is operably magnetically coupled to storage layer **130** of MTJ element **111**, and is configured to generate an external magnetic field F exerting a magnetic force that allows external magnetic field F to serve as the magnetic biasing force utilized to reset and/or switch storage magnetic orientation M_{130} during reset and/or read operating phases. In the disclosed embodiment, field line structure **140** comprises an elongated metal structure that is coupled to a voltage source V_{140} by a conductor

115-21 and to a field line control sub-circuit **175** by way of a conductor **115-22**, and field line sub-circuit **175** is configured to actuate field line structure **140** to generate field F by way of generating a field line current I_{140} through field line structure **140**, whereby a magnetic direction of the magnetic field F is changeable by way of changing the flow direction of field line current I_{140}. As described in additional detail below, this arrangement facilitates switching storage magnetic orientation M_{130} between the parallel and anti-parallel directions relative to reference magnetic orientation M_{120} when MTJ temperature T_{111} is above storage blocking temperature T_{B130}, and may be used in either or both of the reset and readout phases of the sensor operating cycle. Although on-chip field line **140** may be required for the operations of gas sensor **100** described below, in some embodiments (not shown) suitable alternative magnetic bias forces that are utilized during the reset and/or gas sensing phases may be generated from off-chip sources, and in such embodiments field line **140** may be omitted.

Referring to the lower left portion of FIG. **1**, according to another embodiment, gas sensor **100** further includes an on-chip resistive heating element **145** that is physically spaced from field line structure **140** by an intervening dielectric or insulating structure (not shown), is operably thermally coupled to MTJ element **111** and to gas sensing element **150**, and is configured to generate control heat H_{145}. In the disclosed embodiment, heating element **145** comprises a coil structure that is formed using polycrystalline silicon or Tungsten that is coupled to a voltage source V_{145} by a conductor **115-31** and to a heating element control sub-circuit **177** by way of a conductor **115-32**, and heating element control sub-circuit **177** is configured to actuate heating element **145** by way of generating a heater current I_{145} from voltage source V_{145} through heating element **145**. As set forth below, heating element control sub-circuit **177** is configured to actuate heating element **145** during the reset and readout operating phases such that control heat H_{145} increases/decreases the temperatures of MTJ element **111** and gas sensing element **150** to create desired operating temperatures on gas sensor **100**. In one embodiment, the actuation of heating element **145** is controlled using a temperature sensor **147** that is coupled between a voltage source V_{147} and heating element control sub-circuit **177**, and is configured using known techniques such that a temperature sensor control current I_{147} passing through temperature sensor **147** provides heating element control sub-circuit **177** with real-time temperature data usable for controlling heating element **145** to generate the desired operating temperatures. Although on-chip heating element **145** may be required for the operations of gas sensor **100** described below, in some embodiments (not shown) the required control heat may be generated from off-chip heat sources, and in such embodiments heating element **145** may be omitted.

FIG. **2** is a flow diagram depicting an exemplary sensor operating cycle implemented by gas sensor **100** (FIG. **1**) during normal operating conditions according to another embodiment of the present invention. As indicated along the left edge of FIG. **2**, the sensor operating cycle is generally divided into a reset phase, a gas sensing phase, a readout phase, and an optional output processing (OP) phase that are performed sequentially as indicated by the TIME arrow located along the left edge of FIG. **2**. Also included in FIG. **2** are references to the various sub-circuits of control circuit **170** (FIG. **1**) that function as described below during the various phases of the operating cycle. In addition, exemplary operation cycle phases are described with reference to FIG. **2** are depicted with reference to gas sensor **100** in a simplified form in FIGS. **3**(A) through **3**(F), wherein the notation "t[xy]" next to the reference number "**100**" denotes relative time and alternative operating conditions. For example, FIG. **3**(A) depicts gas sensor **100** at an initial time t1, which is indicated by the notation "**100**(*t***1**)", and FIGS. **3**(C) and **3**(D) depict gas sensor **100** at a subsequent time t3 under two different operating conditions, which are indicated by the notations "**100**(*t***3***a*)" and "**100**(*t***3***b*)". Similarly, various signals and magnetic orientations include the time-indicating suffix "-x" indicating a state of the signal/orientation at the associated time period (e.g., MTJ temperature T_{111-1} in FIG. **3**(A) denotes MTJ temperature T_{111} at time t**1**). The time sequence notation is intended merely to denote the relative operation sequence, and is not intended to denote a uniform time period between each depicted operation process. Note that, as described below, the present invention is preferably implemented using multiple series-connected MTJ elements in order to produce high resolution quantitative gas concentration level information. As such, although the sensor operating cycle depicted in FIG. **2** is described in a simplified form with reference to single-MTJ-element gas sensor **100**, the methodology set forth in FIG. **2** is understood to also apply to gas sensors utilizing multiple series-connected MTJ elements.

Referring to the upper left portion of FIG. **2**, the sensor operating cycle begins with the reset phase, which functions to initialize (fix) the resistance state of MTJ element **111** in an initial (first) resistance value. Note that the exemplary embodiment implements a low initial resistance state (i.e., parallel magnetic orientation between the reference and storage layers) to facilitate using AMV or STT to cause switching during the subsequent gas sensing phase, which is preferred for reasons set forth below, but an initial high resistance state (i.e., anti-parallel magnetic orientation) may also be used, but this would require an applied external field to generate switching during the gas sensing phase.

Referring to the upper left portion of FIG. **2**, the reset phase includes increasing MTJ temperature T_{111} above storage blocking temperature T_{B130} (block **211**), applying a magnetic bias force having the desired initial magnetic direction (block **213**), then decreasing MTJ temperature T_{111} below storage blocking temperature T_{B130} (block **215**). This three-stage process for fixing storage magnetic orientation M_{130} in the desired initial (parallel) direction may be accomplished using various techniques. In the exemplary (and presently preferred) embodiment indicated in FIG. **2**, the heating/cooling processes (blocks **211** and **215**) are positioned under the heading HEATING ELEMENT CONTROL SUB-CIRCUIT **177** to indicate that these processes are implemented by heating element **145** of gas sensor **100** (FIG. **1**), and the applied bias force process (block **213**) is positioned under the heading FIELD LINE CONTROL SUB-CIRCUIT **175** to indicate that the applied bias force is generated by field line structure **140** of gas sensor **100** (FIG. **1**). As indicated in FIG. **3**(A), the required control heat H_{145-1} is generated by activating heating element **145** using an applied heater current I_{145-1}, and the required magnetic bias force is generated by applying a field line current I_{140-1} to field line structure **140** such that it generates a (first) external magnetic field F**1** having the desired magnetic direction (indicated by the curved dashed-line arrow pointing left in FIG. **3**(A)). Subsequent cooling of MTJ element **111** below storage blocking temperature T_{B130} is implemented in the exemplary embodiment by de-activating heating element **145** (i.e., terminating heater current I_{145-1}), whereby heat transfer from MTJ element **111** to adjacent

cooler structures causes MTJ temperature T_{111} to decrease. In alternative embodiments (not shown), other heat sources (e.g., adjacent MTJ elements) may be utilized to generate the required heat energy, and the cooling process may be enhanced, by way of heat sink structures. Moreover, applying the required magnetic bias force may be implemented using other structures and/or applied in a direction opposite to the exemplary (parallel) direction. For example, a spin torque transfer generated by reference layer **120** may be used to fix storage magnetic orientation M_{130} in an initial anti-parallel direction relative to reference magnetic orientation M_{120}. In view of these options, it is understood the appended claims are not limited to the exemplary embodiment unless otherwise specified.

After the storage magnetic orientation is fixed in its initial direction (i.e., after MTJ temperature T_{111-1} falls below storage blocking temperature T_{B130} per block **215**), the initial magnetic bias force used to set storage magnetic orientation M_{130} in the initial direction is no longer needed. Referring again to the central column of FIG. **2**, because this initial magnetic bias force is generated by way of activating the field line structure to generate external magnetic field F (block **213**), terminating the magnetic bias force is implemented by de-activating the field line structure, which is depicted in FIG. **3**(B) by way of the absence of a field line current applied to field line structure **140**. In the case where spin torque transfer is used to reset the storage magnetic orientation, terminating this force is not possible, so the terminate process of block **216** is considered optional.

Referring block **217** on the right side of FIG. **2**, in one embodiment an initial resistance value R_{111-2} of MTJ element **111** is determined at the end of the reset phase to facilitate correlated double sampling (CDS) readout operations. Note that block **217** is located under the heading MTJ ELEMENT CONTROL SUB-CIRCUIT **171**/**172** to indicate that this process is implemented by way of utilizing MTJ element measurement circuit **171** and current sensor **172** (both shown in FIG. **1** and described above). FIG. **3**(B) depicts gas sensor **100**(*t***2**) during an exemplary initial readout process during which MTJ element **111** is coupled to a fixed read voltage (i.e., V_{111}, shown in FIG. **1**), and the resulting read current I_{111-2} passing through MTJ element **111** is measured that indicates initial resistance R_{111-1}. Note that, because storage magnetic orientation M_{130-2} remains fixed in the initial parallel direction relative to reference magnetic orientation M_{120}, initial resistance R_{111-1} of MTJ element **111** has a relatively low resistance value (indicated as "R_{MIN}" in FIG. **3**(B)). In addition, according to a presently preferred embodiment, the initial readout process is conducted after MTJ element has cooled substantially to room temperature (indicated in FIG. **3**(B) by "T_{111-2}=RT") before measuring read current I_{111-2}.

As indicated along the left side of FIG. **2**, the gas sensing phase is performed at the end of the resent phase. The gas sensing phase generally involves maintaining MTJ element **111** at a temperature below storage blocking temperature T_{B130} while applying a magnetic bias force corresponding to the anti-parallel direction of the reference and storage layer magnetizations in the MTJ element, where gas sensor **100** is configured such that the presence of target gas G above (i.e., equal to or greater than) a predetermined minimum concentration level will cause gas sensing element **150** to generate sufficient reaction heat H_{150} to raise MTJ temperature T_{111} above storage blocking temperature T_{B130}, thereby causing storage magnetic orientation M_{130} to switch from the parallel to the anti-parallel direction. As discussed below, each of the two operating parameters required to affect the gas sensing phase (i.e., proper MTJ temperature and applied magnetic bias field) may be achieved by alternative methodologies, and as such the illustrated examples described below are not intended to be limiting.

Referring to FIG. **2** and to FIGS. **3**(A) and **3**(B), in the illustrated embodiment maintaining MTJ element **111** at a temperature slightly below storage blocking temperature T_{B130} in the illustrated embodiment is achieved by actuating heating element **145** to generate control heat H_{145-3} in an amount that increases (i.e., when starting from a lower temperature) and maintains MTJ temperature T_{111-3} at an optimal predetermined gas sensing, which is referred to herein as a work point temperature. As explained in additional detail below with reference to FIG. **8**, the work point temperature of a given sensor arrangement coincides with the lowest temperature at which reaction heat H_{150-3} is generated by gas sensing element **150** in response to target gas G, and storage blocking temperature T_{B130} of MTJ element **111** is set an amount above the work point temperature such that gas sensing element **150** generates an amount of reaction heat H_{150-3} that increases MTJ temperature T_{111-3} from the work point temperature to storage blocking temperature T_{B130} when target gas G is present at the predetermined minimum concentration level. By way of illustrative example, FIGS. **3**(C) and **3**(D) show two gas alternative sensing phases, with gas sensor **100**(*t***3***a*) in FIG. **3**(C) disposed in an environment E**1** including target gas G at a relatively low gas concentration level C**1**, and gas sensor **100**(*t***3***b*) in FIG. **3**(D) disposed in an environment E**2** including target gas G at a relatively high gas concentration level C**2**. In both cases, heating element **145** receives the same heater current I_{145-3} such that the same amount of control heat H_{145-3} is generated in both FIGS. **3**(C) and **3**(D). In the case illustrated in FIG. **3**(C), because currently measured gas concentration level C**1** of target gas G is below the predetermined minimum gas concentration level, the combination of reaction heat H_{150-4a} generated by gas sensing element **150** and control heat H_{145-3} generated by heating element **145** fails to increase MTJ temperature T_{111-3b} from the work point temperature to storage blocking temperature T_{m30}, whereby storage magnetic orientation M_{130-3a} remains fixed (i.e., remains in the initial parallel direction relative to reference magnetic orientation M_{120}), and resistance state R_{111} of MTJ element **111** retains its initial low resistance value. In contrast, as illustrated in FIG. **3**(D), when currently measured gas concentration level C**2** of target gas G is above the predetermined minimum gas concentration level, reaction heat H_{150-4b} generated by gas sensing element **150** combines with control heat H_{145-3} to increase MTJ temperature T_{111-3b} from the work point temperature to a temperature above storage blocking temperature T_{B130}, thereby unpinning storage layer **130** such that magnetic bias force AMV/STT/F**2** biases storage magnetic orientation M_{130-3b} into the anti-parallel (second) direction relative to reference magnetic orientation M_{120}, whereby resistance state R_{111} of MTJ element **111** switches from the initial low resistance value to a high resistance value. The work point temperature is generally determined by heating element **150** and the target gas type (i.e., for a given gas sensor, the work point temperature changes for different target gasses). Similarly, as discussed in additional detail herein, the storage blocking temperature T_{B130} for a given MTJ element **111** is generally fixed (unchangeable) after fabrication, but may be influenced during fabrication by random factors (e.g., crystal grain size) and different design parameters (e.g., lateral size and layer thickness). Therefore, the predetermined gas concentration level for gas sensor **100** is the target gas concen-

tration level at which heating element **150** generates the amount of reaction heat H_{150} required to increase MTJ temperature T_{111} from the work point temperature to storage blocking temperature T_{B130}, and therefore is adjustable either by way of altering heating element **150** (i.e., configuring heating element **150** such that the work point temperature is set at an optimal temperature for a given storage blocking temperature), or by altering MTJ element **111** (i.e., by configuring MTJ element **111** such that storage blocking temperature T_{B130} occurs at an optimal temperature for a given work point temperature).

Although increasing/maintaining MTJ element **111** at the work point temperature involves actuating on-chip heater **145** in a preferred embodiment, achieving/maintaining the work point temperature may be achieved using other methods. For example, in cases where the work point temperature may be room temperature, no control heat would be needed to maintain MTJ element at room temperature. In other cases, an off-chip heat source may be used to maintain gas sensor **100** at the work point temperature. Accordingly, unless specified in the appended claims, maintaining MTJ element **111** at the work point temperature during the gas sensing phase should not be limited to generating control heat using an on-chip heating element such as heating element **145**.

Turning to the applied magnetic bias force parameter that is required to perform the gas sensing phase, as illustrated in FIGS. **3**(C) and **3**(D), a benefit of initializing storage layer in the low resistance state is that AMV (discussed above) could be utilized to provide the applied magnetic bias force during the gas sensing phase. In this case, the exchange interaction of the reference and storage layers serves the function of the external magnetic force. MTJ elements are switched into the high resistance state (antiparallel orientations of storage and reference layer magnetizations) due to the magnetic interaction of the reference layer with the storage layer. This benefits gas sensing operation because it allows gas sensor **100** to perform gas sensing at zero operating voltages (i.e., other than the heater currents) by way of eliminating the need for an externally generated magnetic bias force. Switching of the storage layer can be facilitated by using external magnetic fields at the stage of sensing (if the exchange bias from the reference is not sufficient to switch the storage layer). In this case, e.g., spin torque transfer can be used. Alternatively, as indicated by block **223** in FIG. **2** and in FIGS. **3**(C) and **3**(D), in the case where AMV and STT are not available in sufficient strength to produce reliable switching, the magnetic bias force applied to MTJ element **111** during the gas sensing phase may be applied in the form of a (second) external magnetic field F**2** generated by way of passing a field line current I_{140-3} in a direction opposite to reset field line current I_{140-1} (see FIG. **3**(A)), whereby external magnetic field F**2** biases storage layer **130** in the anti-parallel direction to facilitate switching of MTJ element **130** when the measured target gas concentration is above the predetermined minimum concentration level. In yet another embodiment, two or more of AMV, spin torque transfer STT and external magnetic field F**2** are utilized in combination to produce a reliable magnetic bias force during the gas sensing phase.

Referring to the lower portion of FIG. **2**, a readout phase of the sensor operating cycle is performed after completion of the gas sensing phase. As indicated in block **231**, in cases where control heat is used to maintain MTJ element **111** at the work point temperature, the readout phase begins by terminating the production of control heat, thereby allowing MTJ temperature to drop to a low temperature that precludes further detection of the target gas. In cases where external magnetic field F**2** is utilized during the gas sensing phase, it is then terminated (block **233**). The presence of target gas G above the predetermined minimum gas concentration level is then determined, for example, by way of reading the final resistance state of MTJ element **111** (block **217**). Referring to FIGS. **3**(E) and **3**(F), in one embodiment this readout process is performed by re-coupling MTJ element **11** to the fixed read voltage source (i.e., voltage V_{111}, see FIG. **1**), and then measuring the resulting read current I_{111-4x} (i.e., current I_{111-4a} if FIG. **3**(E) and current I_{111-4b} in FIG. **3**(F)) passing through MTJ element **111**. In addition, according to a presently preferred embodiment, the initial readout process is conducted after MTJ element has cooled substantially to room temperature (indicated in FIGS. **3**(E) and **3**(F) by "T_{111-4}=RT") before measuring read current I_{111-4x}. As indicated in FIG. **3**(E), when the final resistance state R_{111-4a} has not switched (e.g., when the resistance value of final resistance state R_{111-4a} remains low/R_{MIN} because storage magnetic orientation M_{130-4a} remains parallel to reference magnetic orientation M_{120}), read current I_{111-4a} has a relatively high current level. Conversely, as indicated in FIG. **3**(F), when the final resistance state R_{111-4b} switched (e.g., when the resistance value of final resistance state R_{111-4a} is high/R_{MAX} because storage magnetic orientation M_{130-4b} switches to an anti-parallel direction relative to reference magnetic orientation M_{120}), corresponding read current $I_{1111-4b}$ has a relatively low current level. Thus, the final resistance values R_{111-4a} and R_{111-4b} in each case can be determined by way of determining the high/low current level of corresponding read currents I_{111-4a} and I_{111-4b}.

Referring to the bottom of FIG. **2**, in one embodiment on-chip circuitry (e.g., gas level processing sub-circuit **173**, see FIG. **1**) is utilized to generate measured gas concentration level data in accordance with the switched/non-switched final resistive state R_{111} determined during the readout phase. As indicated in FIG. **1**, in one specific embodiment, gas level processing sub-circuit **173** configured to receive read current measurement data from MTJ element measurement sub-circuit **171**, to determine the high/low resistance state of resistance state R_{111} using the read current measurement data, and then to generate measured gas concentration level data is generated in a form that can be transmitted (output) to and utilized by an external system. In another embodiment, the final resistance value may be determined by way of comparing the final read current (i.e., currents I_{111-4a} or I_{111-4b}, shown in FIGS. **3**(E) and **3**(F), respectively) with the initial read current I_{111-2} (FIG. **3**(B)) generated at the end of the reset phase to determine whether the final resistance state of MTJ element **111** had switched during the gas sensing phase.

FIG. **4** is a simplified cross-sectional view showing a gas sensor **100**A according to an exemplary practical embodiment of the present invention. Gas sensor **100**A is functionally essentially identical to gas sensor **100** of FIG. **1**, so for brevity various simplifications are utilized to minimize repeating description provided above. For example, various elements of gas sensor **100**A that are functionally identical to corresponding elements of gas sensor **100** are identified using the same reference number with the postscript letter A (e.g., MTJ element **111**A of gas sensor **100**A is understood as being functionally and structurally the same as MTJ element **111** of gas sensor **100**), and it is understood that details provided above regarding elements of gas sensor **100** apply to the corresponding elements of gas sensor **100**A. In addition, the control circuit of gas sensor **100**A is referenced as including frontend circuit structures **170**A-**1** and backend

structures **170**A-**2** for reasons explained below, but it is understood that the control circuit of gas sensor **100**A includes the same sub-circuits discussed above with reference to gas sensor **100**.

Referring to FIG. **4**, sensor **100**A differs from gas sensor **100** in that gas sensing element **150**A and MTJ elements **111**A are fabricated on a membrane structure **135**A utilizing a modified CMOS fabrication flow that achieves superior performance by providing thermal isolation between the high reaction temperatures occurring at gas sensing element **150**A and the current measurement transistors forming the control circuit of gas sensor **100**A. Specifically, frontend structures **170**A-**1** of the control circuit (e.g., NMOS and CMOS transistors) are fabricated on a bulk monocrystalline silicon substrate **301**A using substantially standard CMOS frontend processing techniques in a region (lateral area) of the CMOS IC structure forming gas sensor **100**A that is identified in FIG. **4** as "CMOS AREA", and then backend structures **170**A-**2** of the control circuit (e.g., metallization lines, vias and contacts) are fabricated in a back end stack **310**A formed on the silicon substrate **301**A over the frontend structures **170**A-**1**, also in accordance with standard CMOS fabrication techniques. The standard CMOS backend process flow and, in some cases, the latter part of the standard CMOS frontend process flow, is/are modified to facilitate fabricating MTJ element **111**A, gas sensing element **150**A, field line structure **140**A, heating element **145**A, and any other sensor elements (e.g., temperature sensors) that function to generate the thermal-reaction-type gas sensing operation in separate lateral area of the CMOS IC structure identified in FIG. **4** as "GAS SENSING AREA" that is disposed next to region CMOS AREA. In one embodiment, heating element structure **145**A is fabricated on FOX or STI **304**A on an upper surface **302**A of bulk silicon substrate **301**A using the same materials that are used in front end processing (e.g. polycrystalline silicon, Titanium (Ti), Tungsten (W), silicoses, etc.) that are used during frontend processing, then (third) metal lines **115**A-**31** and **115**A-**32** are formed, e.g., using metallization layer M**1**, that extend between regions GAS SENSING AREA and CMOS AREA (i.e., onto membrane structure **305**A) to provide signal lines for transmitting heater current I_{145A} between the CMOS control circuit (e.g., frontend structures **170**A-**1**) and heating element **145**A. Field line structure **140**A is formed in back end stack **310**A over heating element **145**A using one of the metallization layers (e.g., M**1** or M**2**) between passivation layers, and (second) metal lines **115**A-**21** and **115**A-**22** are formed, e.g., using metallization layers M**1** to M**3**, that extend between regions GAS SENSING AREA and CMOS AREA (i.e., onto membrane structure **305**A) to provide signal lines for transmitting field line current I_{140A} between frontend structures **170**A-**1** and field line structure **140**A. MTJ element **111**A is then formed, along with (first) metal lines **115**A-**11** and **115**A-**12** that extend across membrane structure **315**A to provide signal lines for transmitting read current I_{111A} between frontend structures **170**A-**1** and MTJ **111**A. Finally, gas sensing element **150**A is formed on an upper surface **311**A of back end stack layer **310**A, over MTJ element **111**A. After backside processing is completed, a cavity **305**A is formed below lateral area GAS SENSING AREA by way of wet or dry etching through a lower substrate surface **303**A of bulk silicon substrate **301**A, with the etching controlled to stop at FOX or STI **304**A disposed below heating element **145**A, whereby the portion of back end stack **310**A located over cavity **305**A defines thermally isolated membrane structure **315**A. In the embodiment shown in FIG. **4**, membrane structure **305**A is formed as a closed-type membrane, which minimizes the number of process steps needed to form the membrane structure. In an alternative embodiment (not shown), a suspended membrane structure is formed using an additional mask that is required to form holding arms that suspend the membrane structure. In either case, membrane structure **315**A is formed with a small thermal mass that facilitates rapidly setting the temperature of sensor **100**A, and also serves to avoid heating control circuitry **170**A-**1** during sensor operation. Moreover, because gas sensor **100**A is fabricated using only a few changes to otherwise standard CMOS fabrication process flow, gas sensor **100**A is produced at substantially lower cost than conventional SOI-based gas sensors. That is, although the fabrication of MTJ sensing elements during back end processing of a core CMOS process flow requires the addition of three masks to the core CMOS process flow, this modification is significantly less than the cost of using SOI substrates as a starting material, and thus allows fabricating gas sensors that not only have performance advantages over conventional devices, but are also cheaper than competing solutions.

FIG. **5** is a simplified perspective view showing a semiconductor gas sensor **100**B including two MTJ elements **111**B-**1** and **111**B-**2** that are configured in the manner described above with reference to MTJ element **111** (FIG. **1**) and are operably coupled to a gas sensing element **150**A such that, similar to the first embodiment mentioned above, each MTJ element **111**B-**1** and **111**B-**2** switches its associated resistance state (R_{111B-1} and R_{111B-2}, respectively) in response to an ambient concentration level C of a target gas G in an environment E containing gas sensor **100**B. For example, MTJ element **111**B-**1** includes a storage layer **130**B-**1** separated from a reference layer **120**B-**1** by a tunnel dielectric layer **114**B-**1**, where storage layer **130**B-**1** and reference layer **120**B-**1** comprise multi-layer structures configured to switch from an initial magnetic orientation (e.g., parallel) to an opposite (e.g., anti-parallel) magnetic orientation when gas sensing element **150**A is exposed to target gas G having a concentration level above a predetermined concentration level. Gas sensor **100**B also includes a control circuit **170**B that is configured to implement an operating cycle similar to that described above in order to determine final resistance values of resistance states R_{111B-1} and R_{111B-2} after each gas sensing phase, for example, by way of controlling a field line structure **140**B and a heating element **145**B that are constructed and function in a manner similar to that described above with reference to gas sensor **100**.

According to a novel feature of gas sensor **100**B, gas sensor **100**B is configured such that, during the gas sensing phase of the sensor operating cycle, resistance state R_{111B-1} of MTJ element **111**B-**1** switches at a relatively low (first) corresponding target gas concentration level, and resistance state R_{111B-2} of MTJ element **111**B-**2** switches at a relatively high (second) target gas concentration level—that is, MTJ element **111**B-**1** switches at a corresponding gas concentration level that is different from that of MTJ element **111**B-**2**. By configuring gas sensor **100**B such that MTJ elements **111**B-**1** and **111**B-**2** switch at different corresponding gas concentration levels, gas sensor **100**B is configured to quantitatively determine an actual (i.e., currently measured) gas concentration level to within gas concentration level range defined by the respective switching concentration levels at which MTJ element **111**B-**1** and **111**B-**2** switch their resistance states. That is, as explained below with reference to FIGS. **7**(A) to **7**(C), identifying the switched/not-switched status of each MTJ element **111**B-**1** and **111**B-**2** after a gas sensing phase indicates whether the actual gas concentration

level is below the relatively low target gas concentration level at which MTJ element **111**B-**1** switches its resistance state, between the relatively low and relatively high target gas concentration levels at which MTJ elements **111**B-**1** and **111**B-**2** respectively switch resistance states, or above the relatively high target gas concentration level. This concept is also scalable to provide highly accurate gas concentration level measurements by way of increasing the number of MTJ elements that switch resistance states at respective different gas concentration levels, and setting the respective different gas concentration levels such that the gas concentration range between each adjacent pair of respective different gas concentration levels is vanishingly small (i.e., such that the difference between the storage blocking temperatures of the MTJ elements is very small).

According to a novel feature of gas sensor **100**B, field line structure **140**B is operably magnetically coupled to both MTJ elements **111**B-**1** and **111**B-**2** such that, when actuated, field line structure **140**B generates a magnetic field F having a sufficiently strong magnetic bias force to simultaneously bias the storage magnetic orientations of the storage layers of both MTJ elements **111**B-**1** and **111**B-**2** in accordance with a magnetic direction of magnetic field F. In one embodiment, shared field line structure **140**B consists of a single integral metal structure that extends linearly under the MTJ elements **111**B-**1** and **111**B-**2**, and is controlled by way of an applied read line current I_{140} generated by field line control sub-circuit **175**B of control circuit **100**B. Because a single magnetic field F simultaneously controls both MTJ elements **111**B-**1** and **111**B-**2**, field line structure **140**B is effectively “shared” by MTJ elements **111**B-**1** and **111**B-**2**, and therefore differs from other MTJ arrangements (e.g., magnetic logic unit (MLU) devices that require separately controlled field lines for each MTJ element). Note that the “shared” field line arrangement utilized by gas sensor **100**B is expandable to any number of MTJ elements by aligning the MTJ elements linearly and/or by configuring “shared” field line structure **140**B to apply a common magnetic bias force onto all of the MTJ elements. By utilizing shared field line structure **140**B to control MTJ elements **111**B-**1** and **111**B-**2** (or a larger number of MTJ elements), only a single field line control signal is required to control multiple MTJ elements during the gas sensor’s operating cycle, thereby reducing control circuit complexity. Further, because any number of MTJ elements can be controlled using a single shared field line, gas sensors of the present invention implementing this shared field line approach are scalable to include any number of MTJ elements without requiring additional signal lines or other modifications to the control circuitry, thereby facilitating scalable quantitative gas concentration measurement resolution without increasing operating complexity. Of course, multiple field lines could be used in place of shared field line **140**B, each controlling one MTJ element.

Note that gas sensor **100**B differs from gas sensor **100** (FIG. **1**) in that gas sensing element **150**B is not necessarily restricted to a thermal-reaction-type gas sensing element, and may be implemented using one or more a chemical-reaction-type gas sensing elements. In each case, gas sensing element **150**B is operably coupled to MTJ elements **111**B-**1** and **111**B-**2**, and functions to effect resistance state switching in response to corresponding gas concentration levels. In the case where gas sensing element **150**B is implemented using one or more thermal-reaction-type gas sensing element, gas sensing element **150**B is operably thermally coupled to MTJ elements **111**B-**1** and **111**B-**2**, and reaction heat generated by gas sensing element **150**B is used to cause switching of resistance states $R_{111B\text{-}1}$ and $R_{111B\text{-}2}$ of MTJ elements **111**B-**1** and **111**B-**2**, respectively, in a manner similar to that described above with reference to gas sensor **100**. In the case where gas sensing element **150**B is implemented using one or more chemical-reaction-type gas sensing elements, gas sensing element **150**B is operably physically coupled to MTJ elements **111**B-**1** and **111**B-**2** such that changes in the composition or chemical structure of gas sensing element **150**B in response to adsorption of target gas G causes switching of resistance states $R_{111B\text{-}1}$ and $R_{111B\text{-}2}$ of MTJ elements **111**B-**1** and **111**B-**2**, respectively.

According to another novel feature of gas sensor **100**B, MTJ elements **111**B-**1** and **100**B-**2** are disposed in a series-connected NAND-type string **110**B, which in the exemplary embodiment is connected between voltage source V_{110} and ground by way of a select transistor **117**B such that a read current I_{140} passes sequentially through MTJ elements **111**B-**1** and **100**B-**2**. With this arrangement, series-connected string **110**B exhibits a total string resistance R_{110B} that is collectively defined by (i.e., in this example, a sum of) corresponding respective resistance values $R_{111B\text{-}1}$ and $R_{111B\text{-}2}$ of MTJ elements **111**B-**1** and **111**B-**2**. In a manner similar to that described above, control circuit **170**B includes a string control sub-circuit **171**B that functions to generate and measure read current I_{140} during reset and readout operations, thereby providing both an initial string resistance value R_{111BI} and a final string resistance value R_{111BI} that can be used to determine the individual resistance states $R_{111B\text{-}1}$ and $R_{111B\text{-}2}$ of MTJ elements **111**B-**1** and **111**B-**2**. In the illustrated embodiment, control circuit **170**B utilizes a gas sensing processing sub-circuit **179**B including memory devices MD**1** and MD**2** for respectively storing resistance values R_{111BI} and R_{111BI}, a processor P configured to calculate a difference R_{DIFF} between the initial and final resistance values, and a look-up table LUT configured to store predetermined gas concentration level data values SGCLV. With this arrangement, calculated difference value R_{DIFF} (e.g., 0, 1 or 2) is utilized to access a corresponding gas concentration level value stored in lookup table LUT (i.e., less than lower value C**1**, between values C**1** and C**2**, or above value C**2**), and the corresponding gas concentration level value is then transmitted as the output measured gas concentration level data via an output port OP to an external system (not shown).

FIG. **6** shows a thermal-reaction-type semiconductor gas sensor **100**C including two MTJ elements **111**C-**1** and **111**C-**2** that are operably thermally coupled to a thermal-reaction-type gas sensing element **150**A and connected in a series-connected string **110**C. Similar to gas sensor **100**B, each MTJ element **111**C-**1** and **111**C-**2** is consistent with MTJ element **111** of FIG. **1**, and switches its associated resistance state $R_{111C\text{-}1}$ and $R_{111C\text{-}2}$ in response to different ambient target gas concentration level. In addition, gas sensor **100**C includes a shared field line structure **140**C and a shared heating element **145**C that function in the manner described above.

According to a feature of gas sensor **100**C, MTJ elements **111**C-**1** and **111**C-**2** are maintained at substantially identical temperatures during the sensor operating cycle, and are configured to switch at different gas concentration levels by way of having respective storage layers **130**C-**1** and **130**C-**2** that exhibit different storage blocking temperatures $T_{B130C\text{-}1}$ and $T_{B130C\text{-}2}$ respectively (e.g., wherein storage blocking temperature $TB_{130C\text{-}1}$ is 25° C. lower than storage blocking temperature $T_{B130C\text{-}2}$). That is, shared heating element **145**C and gas sensing element **150**A are respectively thermally coupled and otherwise configured to respectively generate

control and reaction heat in a manner similar to that described above, but in this case the heat is generated such that MTJ temperature $T_{111C\text{-}1}$ and $T_{111C\text{-}2}$ of MTJ elements **111**C-**1** and **111**C-**2**, respectively, are maintained at essentially identical temperature levels during the reset and gas sensing phases. Providing MTJ elements **111**C-**1** and **111**C-**2** with different storage blocking temperatures $T_{B130C\text{-}1}$ and $T_{B130C\text{-}2}$ can be achieved by way of intentional and/or non-intentional (inherent) mechanisms. For example, in the exemplary embodiment shown in FIG. **6**, MTJ elements **111**C-**1** and **111**C-**2** are intentionally provided with different storage blocking temperatures $T_{B130C\text{-}1}$ and $T_{B130C\text{-}2}$ by way of controlling the applied fabrication process used to produce gas sensor **100**C such that each MTJ element **111**C-**1** and **111**C-**2** respectively has a different lateral size $W_{111C\text{-}1}$ and $W_{111C\text{-}2}$. In one embodiment, lateral sizes $W_{111C\text{-}1}$ and $W_{111C\text{-}2}$ vary in the range of 100 nm and 500 nm. In other embodiments, different storage blocking temperatures are intentionally achieved by forming MTJ elements having different anti-ferromagnetic (AFM) layer thickness. In yet other embodiments, the MTJ elements are generated using the same processing parameters (e.g., same lateral width and thickness), and inherent blocking temperature distributions, which typically vary in the range of 50-100° C. due to fluctuations of the grain sizes in the AFM layers forming the storage and/or reference layers, are utilized to provide the desired different storage blocking temperatures.

An exemplary operation cycle of gas sensor **100**C is depicted with reference to FIGS. **6** and **7**(A) to **7**(C), where FIG. **6** shows gas sensor **100**C during a reset phase (i.e., at a time t**1**), and FIGS. **7**(A) to **7**(C) depict gas sensor **100**C during alternative gas reaction phases (i.e., at a time t**2** after time t**1**) in which gas sensor **100**C is exposed to three different target gas concentration levels CA**0**, CA**1** and CA**2**, respectively (i.e., FIG. **7**(A) depicts gas sensor **100**C exposed to target gas concentration CA**0** at associated time t**2***a*, FIG. **7**(B) depicts gas sensor **100**C exposed to target gas concentration CA**1** at associated time t**2***b*, and FIG. **7**(C) depicts gas sensor **100**C exposed to target gas concentration CA**2** at associated time t**2***c*).

Referring to FIG. **6**, during the reset phase a first amount of control heat $H_{145\text{-}1}$ is generated (e.g., by actuating heating element **145**C using a first heating current $I_{145\text{-}1}$) such that MTJ temperatures $T_{111C\text{-}1}$ and $T_{111C\text{-}2}$ of MTJ elements **111**C-**1** and **111**C-**2** increase above both associated storage blocking temperatures $T_{B130C\text{-}1}$ and $T_{B130C\text{-}2}$, and then field line structure **140**C is activated (e.g., by way of a first field line current $I_{140\text{-}1}$) to generate a magnetic field F**1**, whereby storage magnetic orientations $M_{130C\text{-}1}$ and $M_{130C\text{-}2}$ of storage layers **130**C-**1** and **130**C-**2**, respectively, are biased into parallel (first) directions relative to reference magnetic orientations M_{120} of reference layers **120**C-**1** and **120**C-**2**. At the end of the reset phase, MTJ elements **111**C-**1** and **111**C-**2** are cooled below both associated storage blocking temperatures $T_{B130C\text{-}1}$ and $T_{B130C\text{-}2}$ (preferably to room temperature), whereby storage magnetic orientations $M_{130C\text{-}1}$ and $M_{130C\text{-}2}$ are fixed in the parallel direction, and an initial resistance value R_{110CI} of series-connected string **110**C is determined, e.g., by way of measuring a read current I_{110CI} that is generated using methods described above (note that read current I_{110CI} is generated after the reset operation, but is indicated in FIG. **6** for reference). In one embodiment, initial resistance value R_{110CI} is stored in an on-chip memory location (e.g., memory device MD**1**, shown in FIG. **5**). In this case, because both MTJ elements **111**C-**1** and **111**C-**2** are fixed in parallel directions, initial resistance value R_{110CI} has a minimum resistance value R_{MIN}.

FIGS. **7**(A) to **7**(C) depict gas sensor **100**C exposed to target gas concentration levels CA**0**, CA**1** and CA**2**, respectively, during alternative gas reaction phases. Referring to FIG. **7**(A), the gas sensing phase involves heating MTJ elements **111**C-**1** and **111**C-**2** to a work point temperature (and subsequently maintaining MTJ elements **111**C-**1** and **111**C-**2** at the work point temperature) while applying a magnetic bias force such that at least one of storage magnetic orientations $M_{130C\text{-}1}$ and $M_{130C\text{-}2}$ switches from the parallel (first) direction to an anti-parallel (second) direction when target gas G is present in environment E in an amount above a predetermined minimum gas concentration level. Increasing/maintaining the temperature of MTJ elements **111**C-**1** and **111**C-**2** to/at the work point temperature involves re-activating heating element **145**C by way of an associated heater current $I_{145\text{-}2}$ such that control heat $H_{145\text{-}2}$ maintains MTJ temperatures $T_{111C\text{-}1}$ and $T_{111C\text{-}2}$ at the work point temperature, which is described in additional detail below with reference to FIG. **8**. Applying the opposite magnetic bias force involves operating gas sensor **100**C such that storage magnetic orientations $M_{130C\text{-}1/2}$ are biased in the anti-parallel direction relative to reference magnetic orientations M_{120} by a magnetic bias force directed opposite to the magnetic bias force applied during the reset phase. In one embodiment, the magnetic bias force utilized during the gas sensing phase is generated using anti-parallel magnetization force AMV, spin torque transfer STT and/or by generating a (second) external field F**2**, where using magnetic force AMV requires configuring MTJ elements **111**C-**1** and **111**C-**2** in the manner described above, and generating a (second) external field F**2** involves, for example, passing a field line current $I_{140\text{-}2}$ along field line **140**C in a direction opposite to field line current $I_{140\text{-}1}$ during the reset phase (see FIG. **6**). Under these conditions, as explained below with reference to the examples shown in FIGS. **7**(A) to **7**(C), at least one of storage magnetic orientations $M_{130C\text{-}1}$ and $M_{130C\text{-}2}$ is caused to switch from the initial parallel direction to the anti-parallel (opposite) direction when target gas G is above the predetermined minimum gas concentration level corresponding to storage blocking temperature $T_{B130C\text{-}1}$ of MTJ element **111**C-**1**.

FIG. **7**(A) shows gas sensor **100**(*t***2***a*) during a first exemplary gas sensing phase in which gas sensing element **150**C is exposed to an environment E**1** containing target gas G in a relatively low (or zero) concentration level CA**0**. As mentioned above, MTJ elements **111**C-**1** and **111**C-**2** are increased/maintained at the work point temperature by way of control heat $H_{145\text{-}2}$ generated by heating element **145**C. Target gas concentration level CA**0** causes gas sensing element **150**C to generate reaction heat $H_{150\text{-}2a}$ that either fails to increase MTJ temperatures $T_{111C\text{-}1}$ and $T_{111C\text{-}1}$ above the work point temperature, or raises MTJ temperatures $T_{111C\text{-}1}$ and $T_{111C\text{-}1}$ by an amount that remains below storage blocking temperature $T_{B130C\text{-}1}$ of MTJ element **111**C-**1**. Because neither MTJ element reaches its storage blockage temperature, storage magnetic orientations $M_{130C\text{-}1}$ and $M_{130C\text{-}2}$ remain fixed in the parallel direction relative to reference magnetic orientation M_{120C} (i.e., resistance states $R_{111C\text{-}1}$ and $R_{111C\text{-}2}$ retain low resistance values).

FIG. **7**(B) shows gas sensor **100**(*t***2***b*) during an alternative (second) exemplary gas sensing phase in which gas sensing element **150**C is exposed to an environment E**2** containing target gas G in a concentration level CA**1** corresponding to the predetermined minimum gas concentration level of MTJ element **111**C-**1**. As in the first example, MTJ elements **111**C-**1** and **111**C-**2** are increased/maintained at the work point temperature by way of control heat $H_{145\text{-}2}$ generated by

heating element **145**C. In this case, target gas concentration level CA**1** causes gas sensing element **150**C to generate reaction heat H_{150-2b} in an amount that raises MTJ temperatures T_{111C-1} and T_{111C-1} to storage blocking temperature $T_{B130C-1}$ of MTJ element **111**C-**1**, whereby the applied magnetic bias force AMV/STT/F**2** causes storage magnetic orientation M_{130C-1} to switch from the parallel direction to the anti-parallel direction relative to reference magnetic orientation M_{120C}, whereby resistance state R_{111C-1} of MTJ element **111**C-**1** changes from its initial low resistance value to a high resistance value. Because MTJ element **111**C-**2** remains below storage blocking temperature $T_{B130C-2}$, resistance state R_{111C-2} retains its initial low resistance value.

FIG. **7**(C) shows gas sensor **100**(*t***2***c*) during an alternative (third) exemplary gas sensing phase in which gas sensing element **150**C is exposed to an environment E**3** containing target gas G in a relatively high concentration level CA**2** corresponding to the predetermined minimum gas concentration level of MTJ element **111**C-**2**. As in the previous examples, MTJ elements **111**C-**1** and **111**C-**2** are increased/maintained at the work point temperature by way of control heat H_{145-2} generated by heating element **145**C. Target gas concentration level CA**2** causes gas sensing element **150**C to generate reaction heat H_{150-2c} in an amount that raises MTJ temperatures T_{111C-1} and T_{111C-1} to storage blocking temperature $T_{B130C-2}$ of MTJ element **111**C-**2**. Because MTJ elements **111**C-**1** and **111**C-**2** both reach temperatures above their respective storage blocking temperatures, both storage magnetic orientations M_{130C-1} and M_{130C-2} switch from parallel to anti-parallel directions relative to reference magnetic orientation M_{120C}, whereby resistance states R_{111C-1} and R_{111C-2} of MTJ elements **111**C-**1** and **111**C-**2** change from low to high resistance values.

After each of the alternative gas sensing phases described above with reference to FIGS. **7**(A) to **7**(C), MTJ elements **111**C-**1** and **111**C-**2** are cooled substantially to room temperature (e.g., until MTJ temperatures T_{111C-1} and T_{111C-2} are approximately 25° C.), and a readout phase is then performed to determine the final string resistance value and to generate/output corresponding measured gas concentration level data. Similar to the readout processes described above, reading final string resistance is achieved by applying a fixed read voltage and measuring the resulting read current. As indicated in FIG. **7**(A), because neither MTJ element **111**C-**1** and **111**C-**2** switched resistance states during the gas sensing phase in response to gas concentration level CA**0**, read current I_{110CFa} generated during the readout phase is substantially at the same high current level as that of read current I_{110CI}, which was generated at the end of reset (see FIG. **6**), so final string resistance value R_{110CFa} is also equal to minimum resistance value R_{MIN}. In contrast, referring to FIG. **7**(B), because MTJ element **111**C-**1** switched its resistance state during the gas sensing phase in response to gas concentration level CA**1**, read current I_{110CFb} has a level that is lower than read current I_{110CI} by an amount corresponding to the increased resistance state of one MTJ element, final string resistance value R_{110CFb} is assigned an intermediate value R_{INT}. Referring to FIG. **7**(C), because both MTJ elements switched resistance states in response to gas concentration level CA**2**, read current I_{110CFc} has a level corresponding to the increased resistance state of two MTJ elements, final string resistance value R_{110CFc} is assigned a maximum resistance value R_{MAX}. Generating and outputting measured gas concentration level data is then generated, for example, using the process described above with reference to gas level processing sub-circuit **179**B (FIG. **5**).

FIG. **8** is simplified graph that relates MTJ temperatures T_{111C-1} and T_{111C-2} and total string resistance R_{110C} during the exemplary gas sensing phase of gas sensor **100**C described above with reference to FIGS. **7**(A) to **7**(C), and in particular illustrates exemplary work point temperature T_{WP} (i.e., zero target gas concentration point) in relation to storage blocking temperatures $T_{B130C-1}$ and $T_{B130C-2}$, and the corresponding measurement range of gas sensor **100**C. As discussed above, work point temperature T_{WP} is generally defined as the lowest temperature at which gas sensing element **150**C (e.g., FIG. **7**(A)) generates reaction heat in response to a selected target gas (i.e., the zero gas concentration level). That is, if gas sensor **100**C is at temperature below the work point temperature, gas sensing element **150**C would not react to the presence of the selected target gas. Also, for sensor **100**C to function properly, MTJ elements **111**C-**1** and **111**C-**2** (e.g., FIG. **7**(A)) must have corresponding storage blocking temperatures $T_{B130C-1}$ and $T_{B130C-2}$ that are above work point temperature T_{WP}. The temperature differences required to change the total string resistance of string **110**C are indicated in FIG. **8** as ΔT**1** and ΔT**2**, where temperature difference ΔT**1** is the difference between work point temperature T_{WP} and storage blocking temperature $T_{B130C-1}$, and is therefore relatively small in comparison to temperature difference ΔT**2** between work point temperature T_{WP} and storage blocking temperature $T_{B130C-2}$. Applying the graphic description of FIG. **8** to the exemplary gas sensing phase of FIG. **7**(A), when gas sensor **100**C is exposed to target gas G below concentration level CA**1** (i.e., level CA**0**), reaction heat $H_{150C-2a}$ generated by gas sensing element **150**C increases MTJ temperatures T_{111C-1} and T_{111C-2} by an amount less than ΔT**1** (i.e., by an amount insufficient to increase from the work point temperature to storage blocking temperature $T_{B130C-1}$), whereby neither MTJ element **111**B-**1** switches its resistance state, leaving string resistance R_{111CFa} at R_{MIN}. Referring to FIG. **7**(B), when gas sensor **100**C is exposed to target gas G at concentration level CA**1**, reaction heat $H_{150C-2b}$ generated by gas sensing element **150**C is sufficient to increase MTJ temperatures T_{111C-1} and T_{111C-2} by amount ΔT**1** from the work point temperature to storage blocking temperature $T_{B130C-1}$, whereby only MTJ element **111**B-**1** switches its resistance state, changing string resistance R_{111CFb} to R_{MIN}. Referring to FIG. **7**(C), when gas sensor **100**C is exposed to target gas G at concentration level CA**2**, reaction heat $H_{150C-2C}$ is sufficient to increase MTJ temperatures T_{111C-1} and T_{111C-2} by amount ΔT**2** from the work point temperature to storage blocking temperature $T_{B130C-2}$, whereby both MTJ elements **111**B-**1** and **111**B-**2** switches resistance states, changing string resistance R_{111CFc} to R_{MAX}.

FIG. **9** depicts a gas sensor **100**D including MTJ elements disposed in three series-connected strings **110**D-**1**, **110**D-**2** and **110**D-**3** that are also connected in parallel between a voltage source V_{110} and a select transistor **117**D. Each string **110**D-**1** includes multiple MTJ elements that are configured to switch at different gas concentration levels (e.g., string **110**D-**1** includes MTJ elements **111**D-**11** to **111**D-**18**, string **110**D-**2** includes MTJ elements **111**D-**21** to **111**D-**28**, and string **110**D-**3** includes MTJ elements **111**D-**31** to **111**D-**38**), where each of the MTJ elements is configured as described above. Gas sensor **100**D also includes a gas sensing element **150**D, a field line **140**D and a heating element **145**D that are depicted in simplified form for clarity. Gas sensor **100**D illustrates one example of how gas sensors of the present invention are readily scalable to provide a range of measurement accuracies by way of increasing the number of MTJ elements in each series-connected string and/or con-

necting multiple series strings in parallel, thereby providing gas sensors capable of measuring very small gas concentration level variations. Note that the total string resistance of each parallel series-connected string **111**D-**1** to **111**D-**3** is collectively defined by a sum of each strings MTJ elements **111**D-**11** to **111**D-**18**, **111**D-**21** to **111**D-**28** and **111**D-**31** to **111**D-**38**, respectively, and that a total resistance of the entire parallel-connected-string structure is also collectively defined by the MTJ elements of the three strings. The parallel-connected-string arrangement also facilitates measuring multiple target gases, where each target gas has a different combustion temperature (i.e., the temperature corresponding to the "0" gas concentration level of FIG. **8**). In this case, gas sensor **100**D may be implemented to measure, for example, three different target gases by way of actuating heating element **145**D to heat the parallel-connected-string structure to a first predetermined gas concentration level optimized to measure a first target gas having a measurement range corresponding to storage blocking temperatures of MTJ elements **111**D-**11** to **111**D-**18** of string **110**D-**1**, then heating the parallel-connected-string structure to a second (higher) predetermined gas concentration level optimized to measure a second target gas having a measurement range corresponding to storage blocking temperatures of MTJ elements **111**D-**21** to **111**D-**28** of string **110**D-**2**, and then heating the parallel-connected-string structure to a third (yet higher) predetermined gas concentration level optimized to measure a third target gas having a measurement range corresponding to storage blocking temperatures of MTJ elements **111**D-**31** to **111**D-**38** of string **110**D-**3**.

FIG. **10** depicts a gas sensor **100**E including a CMOS control circuit **170**E made up of frontend structures **170**E-**1** disposed on a silicon substrate **301**E and backend structures **170**E-**2** disposed in a back end stack **310**E formed on the silicon substrate **301**E, and multiple MTJ elements **111**E-**11** to **111**E-**34** and three gas sensing elements **150**E-**1** to **150**E-**3** respectively disposed in groups on membrane structures **315**E-**1** to **315**E-**3**. Similar to the embodiment described above with reference to FIG. **4**, each membrane structure **315**E-**1** to **315**E-**3** comprises a respective portion of back end stack **310**E and is disposed over a corresponding cavity **305**E-**1** to **305**E-**3** defined in silicon substrate **301**E. In the disclosed embodiment, the groups of MTJ elements respectively disposed on membrane structures **315**E-**1** to **315**E-**3** are series-connected in NAND-type strings **110**E-**1** to **110**E-**3** that are respectively magnetically coupled to shared field line structures **140**E-**1** to **140**E-**3** and thermally coupled to associated heat sensing elements **150**E-**1** to **150**E-**3** and heating elements **145**E-**1** to **145**E-**3**. Specifically, membrane structure **315**E-**1** includes series-connected string **110**E-**1** including MTJ elements **111**E-**11** to **111**E-**14** that are magnetically coupled to shared field line structure **140**E-**1** and thermally coupled to associated heat sensing element **150**E-**1** and heating element **145**E-**1**, membrane structure **315**E-**2** includes string **110**E-**2** including MTJ elements **111**E-**21** to **111**E-**24**, shared field line structure **140**E-**2**, heat sensing element **150**E-**2** and heating element **145**E-**2**, and membrane structure **315**E-**3** includes string **110**E-**3** including MTJ elements **111**E-**31** to **111**E-**34**, shared field line structure **140**E-**3**, heat sensing element **150**E-**3** and heating element **145**E-**3**. In addition, gas sensor **100**E is configured to simultaneously quantitatively measure three different target gases by way of configuring each group of MTJ elements to switch resistance states in response to different storage blocking temperatures, and by configuring each heating element **145**E-**1** to **145**E-**3** to maintain corresponding groups of MTJ elements at a different work point temperature. To optimize the MTJ elements for the different work point temperatures, in one embodiment each group of MTJ elements is formed with a different lateral size. For example, as indicated by the bubbles at the top of FIG. **10**, MTJ element **111**E-**14** is formed with a lateral size $W_{111E\text{-}14}$ that is smaller than lateral size $W_{111E\text{-}24}$ of MTJ element **111**E-**24** in order to provide MTJ element **111**E-**14** with a lower storage blocking temperature $T_{B130E\text{-}14}$ than MTJ element **111**E-**24**, and lateral size $W_{111E\text{-}24}$ of MTJ element **111**E-**24** is smaller than $W_{111E\text{-}34}$ of MTJ element **111**E-**34** to provide MTJ element **111**E-**24** with a lower blocking temperature $T_{B130E\text{-}24}$ than storage blocking temperature $T_{B130E\text{-}34}$ of MTJ element **111**E-**34**. Other approaches mentioned above may also be used to generate MTJ elements having different storage blocking temperatures.

Although the present invention has been described with respect to certain specific embodiments, it will be clear to those skilled in the art that the inventive features of the present invention are applicable to other embodiments as well, all of which are intended to fall within the scope of the present invention.

The invention claimed is:

1. A method for measuring a gas concentration level of a target gas using at least one magnetic tunnel junction (MTJ) element and a thermal-reaction-type gas sensing element, the MTJ element including a reference layer defining a reference magnetic orientation and a storage layer defining a storage magnetic orientation, the thermal-reaction-type gas sensing element being configured to generate reaction heat in an amount proportional to the concentration level of said target gas, said method comprising:

during a reset phase, generating a first amount of control heat such that an MTJ temperature of said MTJ element increases above a storage blocking temperature of said storage layer;

applying a first magnetic bias force such that said storage magnetic orientation is biased into in a first direction relative to said reference magnetic orientation by said first magnetic bias force;

decreasing said MTJ temperature below said storage blocking temperature such that said storage magnetic orientation is fixed in said first direction relative to said reference magnetic orientation; and

during a gas sensing phase following the reset phase, applying a second magnetic bias force while generating a second amount of control heat that maintains said MTJ temperature at a work point temperature such that, when said measured gas concentration level of said target gas is above a predetermined minimum gas concentration level, said reaction heat generated by said gas sensing element increases said MTJ temperature from said work point temperature to said storage blocking temperature,

wherein said second magnetic bias force is generated such that said storage magnetic orientation is biased into in a second direction relative to said reference magnetic orientation by said second magnetic bias force, said second direction being opposite to said first direction such that said storage magnetic orientation switches from said first direction to said second direction when said target gas is above said predetermined minimum gas concentration level.

2. The method of claim **1**,

wherein generating said first amount of control heat comprises activating a resistive heating element that is operably thermally coupled to said MTJ element, and

wherein decreasing said MTJ temperature below said storage blocking temperature comprises de-activating said resistive heating element.

3. The method of claim **2**, wherein generating said second amount of control heat comprises re-activating said resistive heating element.

4. The method of claim **1**, wherein applying said first magnetic bias force comprises activating a field line structure that is operably magnetically coupled to said MTJ element such that said field line structure generates a first magnetic field having sufficient magnetic force to bias the storage magnetic orientation of the storage layer into said first direction relative to said reference magnetic orientation.

5. The method of claim **1**, wherein applying said second magnetic bias force comprises at least one of activating a field line structure that is operably magnetically coupled to said MTJ element such that said field line structure generates a second magnetic field, and configuring said MTJ element such that said reference layer transfers one of an anti-parallel alignment of magnetization vectors (AMV) force and a spin torque transfer that acts as the second magnetic biasing force.

6. The method of claim **1**, further comprising:

during a readout phase following the gas sensing phase, decreasing said MTJ temperature below said storage blocking temperature, and determining a final resistive state of said MTJ element by measuring a first read current passing through said MTJ element; and

generating measured gas concentration level data in accordance with said determined final resistive state.

7. The method of claim **6**, further comprising, after decreasing said MTJ temperature during said reset phase, determining an initial resistive state of said MTJ element by measuring a second read current passing through said MTJ element,

wherein generating said measured gas concentration level data comprises utilizing both said first read current and said second read current.

8. The method of claim **7**, wherein decreasing said MTJ temperature during said reset phase and during said readout phase comprises decreasing said MTJ temperature substantially to room temperature before measuring said second and first read currents, respectively.

9. A method for measuring a gas concentration level of a target gas using a gas sensor including plurality of magnetic tunnel junction (MTJ) element and at least one thermal-reaction-type gas sensing element, each said MTJ element including a reference layer defining a reference magnetic orientation and a storage layer defining a storage magnetic orientation, said thermal-reaction-type gas sensing element being configured to generate reaction heat in an amount proportional to the concentration level of said target gas, said method comprising:

during a reset phase, generating a first amount of control heat such that an MTJ temperature of each of said plurality of MTJ elements temporarily increases above an associated storage blocking temperature of said storage layer of said each of said plurality of MTJ elements, and activating a single field line structure that is operably magnetically coupled to all of said plurality of MTJ elements such that said field line structure generates a first magnetic field having sufficient magnetic force to bias the storage magnetic orientations of the storage layer of all of said plurality of MTJ elements into said first direction relative to said reference magnetic orientation;

during a gas sensing phase following the reset phase, applying a magnetic bias force to each of said plurality of MTJ elements while maintaining said MTJ temperatures at a work point temperature and below said storage blocking temperatures such that when said measured gas concentration level of said target gas is above a predetermined minimum gas concentration level, said reaction heat generated by said gas sensing element increases said MTJ temperatures of said plurality of MTJ elements from said work point temperature above the associated storage blocking temperature of at least one of said plurality of MTJ elements,

wherein applying said magnetic bias force comprises operating said gas sensor such that said storage magnetic orientations are biased into a second direction relative to said reference magnetic orientations by said magnetic bias force, said second direction being opposite to said first direction such that said storage magnetic orientations of said at least one of said plurality of MTJ elements switches from said first direction to said second direction when said target gas is above said predetermined minimum gas concentration level.

10. The method of claim **9**, wherein generating said first amount of control heat comprises activating a resistive heating element that is operably thermally coupled to said plurality of MTJ elements.

11. The method of claim **10**, wherein generating said second amount of control heat comprises re-activating said resistive heating element.

12. The method of claim **9**, wherein generating said magnetic bias force comprises configuring each of said plurality of MTJ elements such that said reference layer of said each MTJ element generates one of an anti-parallel alignment of magnetization vectors (AMV) force or a spin torque transfer configured to bias the storage magnetic orientation of the storage layer of said each MTJ element into said second direction relative to said reference magnetic orientation.

13. The method of claim **9**, wherein generating said magnetic bias force comprises activating said single field line structure such that said field line structure generates a second magnetic field having sufficient magnetic force to bias the storage magnetic orientations of the storage layer of each of said plurality of MTJ elements into said second direction relative to said reference magnetic orientation.

14. The method of claim **9**, wherein said plurality of MTJ elements are disposed in a series-connected string such that a total string resistance of said series-connected string is collectively defined by the corresponding resistance values of said plurality of MTJ elements, and

wherein said method further comprises, during a readout phase following the gas sensing phase, decreasing said MTJ temperatures of said plurality of MTJ elements to room temperature, and then determining a final resistance value of said series-connected string by measuring a first read current passing through said series-connected string.

15. The method of claim **14**, further comprising, before said gas sensing phase, decreasing said MTJ temperatures of said plurality of MTJ elements to room temperature, and determining an initial resistance value of said series-connected string by generating a second read current passing through said series-connected string.

16. A method for measuring a gas concentration level of a target gas using a gas sensor including plurality of magnetic tunnel junction (MTJ) element and at least one gas sensing element, each said MTJ element including a refer-

ence layer defining a reference magnetic orientation and a storage layer defining an associated storage magnetic orientation, wherein said storage layer of each said MTJ element is configured such that each said associated storage magnetic orientation is independently switchable between a parallel direction and an anti-parallel direction relative to said reference magnetic orientation, whereby a corresponding resistance state of said each MTJ element is respectively switchable between a first resistance value and a second resistance value, wherein said plurality of MTJ elements are disposed in a series-connected string such that a total string resistance of said series-connected string is collectively defined by the corresponding resistance values of said plurality of MTJ elements, and wherein said gas sensing element is operably coupled to said plurality of MTJ elements, said method comprising:

during a reset phase, fixing the associated storage magnetic orientations of the storage layers of all of said plurality of MTJ elements into said parallel direction relative to said reference magnetic orientation, and then determining an initial resistance value of said series-connected string by measuring a first read current passing through said series-connected string;

during a gas sensing phase following the reset phase, operating said gas sensor such that said gas sensing element causes a corresponding resistance state of each said MTJ element to switch from one of said first and second resistance values to the other of said first and second resistance values only when said concentration of said target gas in said environment is at least equal to a corresponding concentration level;

during a readout phase following the gas sensing phase, determining a final resistance value of said series-connected string by generating a second read current passing through said series-connected string; and

after said readout phase, generating measured gas concentration level data in accordance with a difference between said initial resistance value and said final resistance value.

17. The method of claim **16**,

wherein, during said reset phase, determining said initial resistance value further comprises measuring said first read current after said plurality of MTJ elements have cooled substantially to room temperature, and

wherein, during said readout phase, determining said final resistance value further comprises measuring said second read current after said plurality of MTJ elements have cooled substantially to room temperature.

18. The method of claim **17**, wherein, during said reset phase, fixing the storage magnetic orientations of the storage layers of all of said plurality of MTJ elements into said parallel direction relative to said reference magnetic orientation comprises activating a resistive heating element that is operably thermally coupled to said MTJ element, and then de-activating said resistive heating element until said MTJ elements have cooled substantially to room temperature.

19. The method of claim **16**, wherein, during said reset phase, fixing the storage magnetic orientations of the storage layers of all of said plurality of MTJ elements into said parallel direction relative to said reference magnetic orientation comprises activating a single field line structure such that said field line structure generates a magnetic field having sufficient magnetic force to bias the storage magnetic orientations of the storage layer of each of said plurality of MTJ elements into said parallel direction relative to said reference magnetic orientation.

20. The method of claim **15**, wherein generating measured gas concentration level data comprises utilizing said difference between said initial resistance value and said final resistance value to access a corresponding gas concentration level data stored on said gas sensor, and then transmitting said corresponding gas concentration level data through an output port to an external system.

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